Is eco-efficiency in greenhouse gas emissions converging among European Union countries?

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Abstract Eco-efficiency refers to the ability to produce more goods and services with less impact on the environment and less consumption of natural resources. This issue has become a matter of concern that is receiving increasing attention from politicians, scientists and researchers. Furthermore, greenhouse gases emitted as a result of production processes have a marked impact on the environment and are also the foremost culprit of global warming and climate change. This paper assesses convergence in eco-efficiency in greenhouse gas emissions in the European Union. Eco-efficiency is assessed at both country and greenhouse-gas-specific levels using Data Envelopment Analysis techniques and directional distance functions, as recently proposed by Picazo-Tadeo et al. (Eur J Oper Res, 220:798–809, 2012). Convergence is then evaluated using the Phillips and Sul (Econometrica, 75:1771–1855, 2007) approach that allows testing for the existence of convergence groups. Although the results point to the existence of different convergence clubs depending on the specific pollutant considered, they signal the existence of at least four clear groups of countries. The first two groups are core European Union high-income countries (Benelux, Germany, Italy, Austria, the United Kingdom and Scandinavian countries). A third club is made up of peripheral countries (Spain, Ireland, Portugal and Greece) together with some Eastern countries (Latvia and Slovenia), while the remaining clubs consist of groups containing Eastern European countries.
Keywords  Eco-efficiency · Convergence · Clubs · Greenhouse gases emissions · European Union · Directional distance functions · Data Envelopment Analysis

JEL classification  C15 · C22 · C61 · F15 · Q54 · Q56

1 Introduction

Global warming and climate change are matters of concern for policymakers, researchers and society as a whole. Many scientists claim that climate change is unequivocal and caused by increasing concentrations of greenhouse gases (GHG) produced by human activities. As a result, international institutions such as the United Nations and the International Energy Agency have agreed on the adoption of large cuts in GHG emissions in order to achieve long-term sustainable development (United Nations 2009; IEA 2011). The Kyoto Protocol was adopted in the context of the United Nations Framework Convention on Climate Change (UNFCCC)\(^1\) in 1997 and came into force in 2005; it established binding targets for reducing GHG emissions for industrialised economies, including the European Union (EU). Before the early nineties, EU policy regarding air pollution was fragmented and only some standards existed for a few air pollutants. However, in 1993 the 5th Environmental Action Program (CEC 1993) established long-term objectives for air quality in Europe in a more integrated way by setting ceilings for some air pollutants, including some GHG such as carbon dioxide (CO\(_2\)). In addition, under the Kyoto Protocol, the members of the older European Union (UE-15) agreed to cut down their collective GHG emissions by 2012 to 8% below the levels recorded in the base year 1990. Later, the 6th Environmental Action Program adopted in 2002 set out the framework for environmental policymaking in the European Union for the period 2002–2012 and also identified climate change as one of the priority areas.

Finally, the EU climate and energy package launched in March 2007 and adopted by the European Parliament in December 2008 consisted of a range of measures to fight against climate change, focused on emissions cuts, the increasing usage of renewables (wind, solar, biomass) and higher levels of energy efficiency.\(^2\) The package established a series of ambitious measures to cut down GHG emissions by 20% below 1990

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\(^1\) The article 2 of UNFCCC, an international environmental treaty promoted in 1992 by the United Nations and currently signed by 194 parties, states that ‘… The ultimate objective of this Convention and any related legal instruments … is to achieve stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient … to enable economic development to proceed in a sustainable manner’.

\(^2\) The core of the package comprises four pieces of complementary legislation. Revision and strengthening of the EU Emissions Trading System (ETS), with a progressive replacement of free allocation of allowances by auctioning, and an extension of the system to new economic activities and gases; the so-called Effort Sharing Decision that establishes binding greenhouse gas emission targets for sectors not included in the ETS; binding national targets for renewable energy; and, finally, a legal framework to promote the development and safe use of carbon capture and storage.
observed levels by 2020\(^3\), while the EU offered to scale up this reduction to 30\% if other developed economies agreed to do their fair share for a global effort. Furthermore, in the longer term the EU has targeted reducing emissions to 80–95\% below 1990 levels by 2050.

The stabilisation or reduction of GHG emissions is one way to combat global climate change and the greenhouse effect caused by an excessively high concentration of atmospheric pollutants. As claimed by Romero-Ávila (2008), achieving this objective implies that there must be some kind of convergence of emissions to a specified target that ensures sustainability. As national programmes on the climate policies of EU members are discussed in the framework of the EU environmental policy and, in most cases, are promoted by European institutions, convergence of policies and measures can be expected, as well as convergence in GHG emissions. In this sense, Albrecht and Arts (2005) presented an empirical analysis of convergence in climate policies and measures (output convergence) and convergence in the effects of such policies (outcome convergence) in 23 European countries. While some output policy convergence was found during the 1994–2002 period, the authors suggest that climate policy outcome convergence did not take place; what is more, huge differences among countries were found. Notwithstanding, they also advise that any conclusion on the lack of outcome convergence should be taken in perspective, given the projections for domestic GHG emissions and national policy effects.

Furthermore, some authors like Kortelainen (2008) or Westerlund and Basher (2008) have stressed that a fair distribution of GHG emissions in the long-run entails the achievement of convergence. Although international agreements on emissions caps are complex and influenced by economic and political factors that interact with each other, convergence on behalf of EU countries could encourage developing countries to accept a cap on their own emissions. Moreover, EU convergence could also help to make progress towards reaching a long-term global agreement to prevent dangerous human interference in the global climate system. Finally, most projection models guiding policymakers in their formulation of emission abatement strategies to combat climate change assume convergence in emissions.

Given the far-reaching policy implications of attaining emissions convergence in the industrialised world, this paper takes on board this issue by analysing convergence in ecological-economic efficiency, also known as eco-efficiency, in GHG emissions among EU countries. Therefore, our empirical research implies two different steps, namely, an accurate measurement of eco-efficiency and a suitable procedure to assess convergence.

As regards the former, the concept of eco-efficiency refers to the ability of firms, industries or economies to produce more goods and services with less impact on the environment and less consumption of natural resources, encompassing both ecological and economic issues. Several international organisations have recognised that assessing eco-efficiency constitutes a powerful instrument capable of providing policymakers with helpful information to design better environmental policies to achieve

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\(^3\) This package implemented the 20–20–20 targets endorsed by European leaders in 2007, according to which by 2020 there should be a reduction of 20\% in GHG emissions compared with 1990, a share of 20\% of renewables in energy consumption, and energy improvement by 20\%. 

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sustainable development (United Nations 2009). In practice, eco-efficiency has been measured by ratios that relate the economic value of goods and services produced to the environmental pressures or impacts involved in production processes, the larger the ratio the greater the eco-efficiency (Schmidheiny and Zorraquin 1996; Huppes and Ishikawa 2005). Regarding GHG emissions, eco-efficiency has been commonly measured by ratios such as GDP over CO₂. Although these simple ratios have the advantage of their straightforwardness and easiness of understanding for policymakers and the general public, they ignore that production processes involve simultaneous emissions of several GHG and also that a given GDP can be obtained with different combinations of air pollutants. In recent years, more sophisticated approaches to assessing eco-efficiency have been developed, including benchmarking techniques in the framework of conventional efficiency analysis. Two prominent papers in this line of research are Kuosmanen and Kortelainen (2005) and Kortelainen (2008), which analysed global eco-efficiency by computing a composite indicator of ecological performance at country-level for 20 EU members.

Here we contribute to the previous literature with an evaluation of eco-efficiency in the emission of GHG for all the members of the EU-27 at both country and air pollutant level. Eco-efficiency is assessed using the recent approach developed by Picazo-Tadeo et al. (2012). Based on Data Envelopment Analysis (DEA) techniques and the so-called directional distance functions, this methodological approach considers several GHG in the computation of the eco-efficiency ratio and, more interestingly, assesses eco-efficiency at country and greenhouse-gas-specific emissions level. By accounting simultaneously for several GHG emissions, we take conventional analyses based on emissions of a single pollutant a step further, thus providing a more comprehensive view of the relationship between the economy and the environment. Furthermore, assessing eco-efficiency at the level of greenhouse-gas-specific emissions could provide European policymakers with sound information that would have remained hidden to more conventional approaches. As explained in detail in Sect. 2.2, our approach permits eco-efficiency assessment under different scenarios representing the preferences of policymakers regarding the trade-off between economic and ecological performance; for instance, we provide an evaluation of the extent to which emissions of a particular gas could be reduced while maintaining economic performance and, moreover, without increasing the emission of other GHGs. In our opinion, gas-specific eco-efficiency assessment could provide policymakers with relevant insight, helping them to design environmental policies aimed at reducing specific GHG emissions in order to combat climate change.

Concerning the issue of convergence, several papers have assessed convergence in GHG emissions using simple ratios such as per capita CO₂ emissions; these include Strazicich and List (2003), Lanne and Liski (2004), Aldy (2006), Aldy (2007), Ezcurra (2007), Westerlund and Basher (2008), Romero-Ávila (2008), Barassi et al. (2008, 2011), Panopoulou and Pantelidis (2009), Marrero (2010), Jobert et al. (2010) and Ordás Criado and Grether (2011). Camarero et al. (2008) tested for convergence in environmental performance using a series of composite indicators computed within the framework of the production theory; these authors analyse convergence among 22 OECD countries during the period 1970–2002, using data on CO₂ emissions as a measure of the impact of economic activity on the environment. Nourry (2009)
tested the hypothesis of stochastic convergence of carbon dioxide and sulphur dioxide by analysing all pairs of per capita emissions gaps across a sample of 127 and 81 countries, respectively. Furthermore, Camarero et al. (2013) have studied convergence clusters in the economic-ecological performance of 22 OECD countries over the period 1980–2008, using data on carbon dioxide, nitrogen oxides and sulphur oxides emissions.

In our paper, we further contribute to this literature by assessing convergence in eco-efficiency in GHG emissions among EU countries using the approach by Phillips and Sul (2007), which tests for the existence of convergence groups sharing common features in terms of their eco-efficiency paths. This methodology is especially well suited for this type of variables, i.e. eco-efficiency, where the concept of absolute convergence and stochastic and/or deterministic convergence can be too demanding. In contrast, testing for convergence clubs can be a more flexible approach, as the clubs correspond to different levels of international eco-efficiency attainment. Convergence clubs can be helpful in examining eco-efficiency in a specific country relative to other countries. These groups help to identify similarities and differences between countries and assist researchers and policymakers in making generalised hypotheses. Unlike most previous studies, the methodology used in the present research identifies groups of countries that converge to different equilibria, allowing individual countries to diverge. In this way, we can examine the relationship between the convergence clusters and various economic characteristics. We can also attempt to identify the reasons why the countries that do not belong to any convergence group have diverged, thereby shedding more light on the factors behind the differences in eco-efficiency among EU countries. These factors include countries’ respective levels of development, the different structures of economic activity and differences in environmental awareness, among others. In fact, eco-inefficient countries should move to cleaner production processes if they wish to catch up with leading European countries; moreover, they should also change their respective production structures towards less contaminating activities. Obviously, examining the economic characteristics that lead to eco-efficiency convergence can be a major issue for policymakers.

In our opinion, jointly assessing eco-efficiency at greenhouse-gas-specific emission and country level for all members of the UE-27, together with analysing convergence by testing for the existence of convergence groups has a genuine academic interest and adds interesting insight into the current literature in this field of research. Moreover, this approach has a great potential to provide European policymakers with relevant information helping them to design better environmental policies regarding GHG emissions and climatic change. From the point of view of policymakers, countries included in a group may require different incentives or policy measures to others placed in an alternative relative position. Identifying potential members of a group and their convergence path may also indicate whether previous decisions have improved their relative position. All in all, the analysis of the convergence process may signal the evolution of eco-efficiency by country group, adding relevant information to policymakers. This could be the case for the former European communist countries that recently entered the EU.
Table 1 Emissions of GHG in the European Union (millions of CO₂ equivalent tons)

|                        | European Union-27 |       | European Union-15 |       |
|------------------------|-------------------|-------|-------------------|-------|
|                        | 1990              | 2009  | 1990              | 2009  |
| Carbon dioxide (CO₂)   | 4,395.7           | 3,765.0 | 3,359.4           | 3,063.2 |
| Nitrous oxide (N₂O)    | 528.3             | 354.9 | 399.1             | 277.4 |
| Methane (CH₄)          | 605.8             | 413.3 | 450.6             | 309.5 |
| Sulphur hexafluoride (SF₆) | 11.0          | 6.5   | 10.9              | 6.1   |
| Hydrofluorocarbons (HFCs) | 28.1           | 72.4  | 28.1              | 65.6  |
| Perfluorocarbons (PFCs) | 20.0             | 2.5   | 16.8              | 1.9   |
| Aggregate emission (GHG) | 5,588.9         | 4,614.6 | 4,264.9           | 3,723.7 |

The rest of the paper is organised as follows. Section 2 is devoted to assessing eco-efficiency; the data and sources of information are described in Sect. 2.1, the main insight provided by the methodology is expounded in Sect. 2.2, while Sect. 2.3 comments on the results. Section 3 focuses on measuring convergence; the methodology is developed in Sect. 3.1 and the results are presented and discussed in Sect. 3.2. A final Section concludes.

2 Assessing eco-efficiency in greenhouse emissions with directional distance functions

2.1 Data and sources of information

The data on GHG used in this research comes from the Annual European Union Greenhouse Inventory 1990–2009 of the European Environmental Agency (EEA 2011). This database includes information about the six main GHG against which reduction targets were agreed in the Kyoto Protocol, including carbon dioxide (CO₂), nitrous oxide (N₂O), methane (CH₄), sulphur hexafluoride (SF₆), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs). Furthermore, data are provided at sector level for all 27 countries currently integrated in the EU-27.

In order to assess eco-efficiency and convergence, in this paper we use information about emissions of carbon dioxide (CO₂), nitrous oxide (N₂O) and methane (CH₄), which jointly represent around 98.5% of aggregated GHG emissions. Concerning GHG-emitting sectors, we use aggregate measures that include emissions from the sectors of energy, industrial processes, solvents and other product use, agriculture, waste and, finally, others; thus, emissions from land use, land use change and forestry, which in most cases are negative, are not considered in our analysis. Finally, our data

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4 Accessed on 25th February 2012 through http://dataservice.eea.europa.eu

5 Although CO₂, CH₄ and N₂O occur naturally, human activities have changed their concentrations in the atmosphere. According to the International Panel for Climate Change (IPCC 2007), between the pre-industrial era (ending about 1750) and 2005, concentrations of these GHG have increased globally by 36, 148 and 18%, respectively.
include all EU-27 countries and cover the period 1990–2009; emissions are measured in millions of tons of CO₂ equivalent. Table 1 displays the extent of GHG emissions in the EU in 1990 and 2009 (information about fluorinated gases, SF₆, HFCs and PFCc is also included to illustrate their relative importance in regard to total GHG emissions).

As already discussed in the Introduction, 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. As displayed in Table 1, this objective is on course to be overachieved, as in 2009 emissions are estimated to have been reduced by 12.7%; however, there are some important differences among countries, e.g. Mediterranean economies such as Spain, Portugal or Greece have actually raised their emissions, with increases of 29, 25 and 17%, respectively. In addition, most of the countries that joined the EU in 2004 and 2007 have also agreed important reduction targets, so the combined reduction of GHG emissions in 2009 for the EU-27 has already reached 17.4% (see Table 1 again).

The economic performance of countries in the EU is accounted for by the value of goods and services produced, which is measured by real Gross Domestic Product (GDP) (millions of US$, base 2000), with data from the World Bank. Table 2 relates GHG emissions to GDP in the EU, thus providing information about the so-called intensity of emissions. First, it can be observed that emissions over GDP have significantly decreased between 1990 and 2009. Accordingly, EU-27 collective GHG emissions have decreased by more than half from 1.91 CO₂ equivalent tons per 1,000 US$ of GDP in 1990 to 0.89 in 2009. The EU-15 has also achieved important reductions, albeit to a lesser extent. In the last two decades, emissions have dropped from 0.72 to 0.45 CO₂ equivalent tons per 1,000 US$. These reductions are particularly important taking into account that the twelve countries that joined the EU in 2004 and 2007 record noticeably higher GHG emissions and that some of the economies that register lower GHG emissions, such as Sweden, the United Kingdom, France, Denmark and Austria, are members of the older EU-15.

2.2 Computing eco-efficiency scores

Let us start the description of the methodology by borrowing the formal definition of eco-efficiency proposed by Kuosmanen and Kortelainen (2005), which, once adapted to the purpose of our research, is expressed as a ratio between GDP and a composite indicator of the GHG emissions generated by production processes:

\[
\text{Eco-efficiency} = \frac{\text{GDP}}{E(\text{CO}_2, \text{N}_2\text{O}, \text{CH}_4)} = \frac{\text{GDP}}{w_{\text{CO}_2}\text{CO}_2 + w_{\text{N}_2\text{O}}\text{N}_2\text{O} + w_{\text{CH}_4}\text{CH}_4} (1)
\]

where \(E\) is a function that aggregates individual GHG emissions into a single emission score. Furthermore, we assume that this function takes the form of a linear weighted average of CO₂, N₂O and CH₄ emissions with weights \(w_{\text{CO}_2}\), \(w_{\text{N}_2\text{O}}\) and \(w_{\text{CH}_4}\), respectively.

\[6\] Accessed on 25th February 2012 through http://databank.worldbank.org
| Country          | GHG | CO₂ | N₂O | CH₄ | Year 2009 | GHG  | CO₂  | N₂O  | CH₄  |
|------------------|-----|-----|-----|-----|-----------|------|------|------|------|
| Austria (Au)     | 0.52| 0.42| 0.04| 0.06| 0.37      | 0.31 | 0.02 | 0.03 |
| Belgium (Be)     | 0.77| 0.64| 0.06| 0.05| 0.48      | 0.42 | 0.03 | 0.02 |
| Bulgaria (Bu)    | 7.65| 5.72| 0.86| 1.06| 3.08      | 2.38 | 0.24 | 0.45 |
| Cyprus (Cy)      | 0.85| 0.68| 0.05| 0.12| 0.77      | 0.66 | 0.03 | 0.09 |
| Czech Republic (Cz)| 3.54| 2.98| 0.22| 0.33| 1.75      | 1.50 | 0.10 | 0.15 |
| Denmark (Dk)     | 0.55| 0.43| 0.08| 0.05| 0.36      | 0.29 | 0.04 | 0.03 |
| Estonia (Es)     | 6.85| 6.05| 0.33| 0.47| 2.05      | 1.74 | 0.12 | 0.17 |
| Finland (Fi)     | 0.71| 0.57| 0.07| 0.06| 0.47      | 0.39 | 0.04 | 0.03 |
| France (Fr)      | 0.52| 0.36| 0.08| 0.06| 0.35      | 0.25 | 0.04 | 0.04 |
| Germany (De)     | 0.81| 0.68| 0.06| 0.07| 0.46      | 0.39 | 0.03 | 0.02 |
| Greece (Gr)      | 1.05| 0.84| 0.10| 0.10| 0.73      | 0.62 | 0.04 | 0.05 |
| Hungary (Hu)     | 2.20| 1.64| 0.29| 0.27| 1.14      | 0.86 | 0.12 | 0.14 |
| Ireland (Ie)     | 1.13| 0.67| 0.18| 0.28| 0.49      | 0.33 | 0.06 | 0.10 |
| Italy (It)       | 0.55| 0.46| 0.04| 0.05| 0.44      | 0.37 | 0.03 | 0.03 |
| Latvia (La)      | 2.55| 1.83| 0.36| 0.36| 0.96      | 0.62 | 0.15 | 0.17 |
| Lithuania (Li)   | 3.12| 2.30| 0.43| 0.40| 1.26      | 0.75 | 0.29 | 0.21 |
| Luxembourg (Lu)  | 1.03| 0.96| 0.04| 0.04| 0.45      | 0.41 | 0.02 | 0.02 |
| Malta (Ma)       | 0.88| 0.78| 0.02| 0.07| 0.65      | 0.57 | 0.01 | 0.06 |
| Netherlands (Nl) | 0.75| 0.56| 0.07| 0.09| 0.46      | 0.39 | 0.02 | 0.04 |
| Poland (Pl)      | 3.84| 3.12| 0.32| 0.39| 1.56      | 1.29 | 0.11 | 0.14 |
| Portugal (Pr)    | 0.68| 0.50| 0.06| 0.12| 0.61      | 0.46 | 0.04 | 0.10 |
| Romania (Ro)     | 5.69| 3.91| 0.76| 0.97| 2.34      | 1.53 | 0.33 | 0.47 |
| Slovak Republic (Sk)| 2.69| 2.28| 0.23| 0.17| 1.00      | 0.81 | 0.08 | 0.10 |
| Slovenia (Sl)    | 1.11| 0.89| 0.08| 0.13| 0.75      | 0.62 | 0.05 | 0.08 |
| Spain (Sp)       | 0.64| 0.51| 0.06| 0.06| 0.51      | 0.42 | 0.04 | 0.05 |
| Sweden (Sw)      | 0.36| 0.28| 0.04| 0.03| 0.21      | 0.16 | 0.02 | 0.02 |
| United Kingdom (UK)| 0.67| 0.51| 0.06| 0.10| 0.34      | 0.28 | 0.02 | 0.03 |

According to the classification of Huppes and Ishikawa (2005), we are adopting a macro-level environmental-productivity ratio approach, such that eco-efficiency improves when GDP relative to the aggregated emission score increases. In addition, we assume there is a technology behind our eco-efficiency ratio, the so-called emissions generating technology (EGT) (see Kuosmanen and Kortelainen 2005; Picazo-Tadeo et al. 2011), which, given the state of knowledge, represents all feasible combinations of GDP, variable $g$, and GHG emissions, represented by vector $e = (\text{CO}_2, \text{N}_2\text{O}, \text{CH}_4)$. This technology is formally expressed as:
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\[ \text{EGT} = \left\{ [g, e = (\text{CO}_2, \text{N}_2\text{O}, \text{CH}_4)] \in \mathbb{R}^4_+ \mid \text{GDP } g \text{ can be generated with emissions } e \right\} \]  

(2)

In addition, the following assumptions are made regarding the EGT: (i) producing goods and services unavoidably entails the emission of some GHG into the environment, such that the only way of not emitting GHG is not producing; (ii) lower GDP can always be obtained with the same level of emissions; (iii) emissions can always be increased for any given GDP; and (iv) any convex combination of two or more feasible (observed) pairs of GDP and GHG emissions is considered to be also feasible, i.e. we assume a convex technology.

Once defined the measure of eco-efficiency and characterised the technology, we may use the recent proposal by Picazo-Tadeo et al. (2012) to assess eco-efficiency, which is based on the computation of directional distance functions with Data Envelopment Analysis (DEA) techniques. Formally, the directional distance function is defined as:

\[ \vec{D} \left[ g, e; d = (d_g, -d_e) \right] = \text{Sup} \left[ \Phi \mid (g + \Phi d_g, e - \Phi d_e) \in \text{EGT} \right] \]  

(3)

with \( d = (d_g, -d_e) \) being the so-called direction vector.

The directional distance function of expression (3) models GDP and GHG emissions jointly, providing a complete representation of the EGT. It is lower bounded to zero (Chambers et al. 1998) and seeks the maximum attainable expansion of production and the largest feasible contraction of emissions, while remaining within the EGT. Accordingly, it inflates GDP in the \( d_g \) direction (inflated GDP is \( g + \Phi d_g \)) and contracts GHG emissions in the \( -d_e \) direction (reduced GHG emissions are \( e - \Phi d_e \)), the latter being negative to capture the fact that emissions are being reduced.

One outstanding feature of directional distance functions is their flexibility, which in the particular case of our research makes it possible to compute a wide range of indicators of eco-efficiency that represent different objectives regarding GHG emissions. These objectives are modelled by means of different assumptions made on the direction vector to approach the technological frontier via alternative paths.

In this framework, let us assume, on the one hand, that researchers and/or policymakers are interested in assessing the extent to which EU-27 countries could proportionally cut down \( \text{CO}_2, \text{N}_2\text{O} \) and \( \text{CH}_4 \) emissions without reducing the value of goods and services produced. These preferences could be modelled by means of the following directional distance function, which assesses what we call here proportional GHG eco-efficiency:

\[ \text{Eco-efficiency}_{\text{GHG}} = \vec{D} \left[ g, e; d = (0, -e) \right] = \text{Sup} \left[ \Phi_{\text{GHG}} \mid (g, (1 - \Phi_{\text{GHG}})e) \in \text{EGT} \right] \]  

(4)

\( d = (0, -e) \) being the direction vector that represents the above-mentioned preferences.

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7 Färe and Grosskopf (2000) summarise the theory and applications of directional distance functions, while Picazo-Tadeo et al. (2005) analyse their utility in the assessment of environmental performance.
Under this particular direction vector, GHG emissions are proportionally contracted in the $-e$ direction, i.e. reduced emissions are $(1 - \Phi_{\text{GHG}})e$, while GDP is maintained at level $g$. The interpretation of the directional distance function in expression (4) is really straightforward: a zero value would point to eco-efficiency while a value of, let us say, 0.3 would mean that, given the EGT, all three GHG emissions, i.e. CO$_2$, N$_2$O and CH$_4$ emissions, could be reduced by 30\% without decreasing GDP.

On the other hand, researchers and/or policymakers might be interested in evaluating how much a particular GHG emission, namely emission $e_i$, could be reduced without increasing the remaining emissions, labelled as $e_{-i}$, while also maintaining the value of goods and services produced. Under this schedule of preferences, the directional distance function that assesses greenhouse-gas-specific eco-efficiency is:

$$\text{Eco-efficiency}_{e_i} = \bar{D}[g, e(e_i, e_{-i}) ; d = (0, -(e_i, 0_{-i}))]$$

$$= \sup \{ \Phi_{e_i} \mid [g, ((1 - \Phi_{e_i})e_i, e_{-i})] \in \text{EGT} \}$$

(5)

where $d = (0, -(e_i, 0_{-i}))$ is the associated direction vector.

Now, the emission of gas $i$ is contracted to $(1 - \Phi_i)e_i$, while GDP and emissions of other gases are maintained at their observed levels $g$ and $e_{-i}$, respectively. Given the assumptions made regarding the EGT, when only one GHG emission is reduced the directional distance function is always equal to or greater than the directional distance function when all GHG emissions are simultaneously reduced, thus indicating greater eco-inefficiencies (see Picazo-Tadeo et al. 2012). Assuming, for example, that the GHG being reduced is CO$_2$, a score of 0.4 for the directional distance function in expression (5) would mean that CO$_2$ emissions could be reduced by 40\% while emissions of N$_2$O and CH$_4$ as well as GDP are maintained at their observed levels.\(^8\)

In practice, the directional distance functions described in expressions (4) and (5) are computed, as already noted, using DEA techniques. Pioneered by Charnes et al. (1978), this non-parametric approach to efficiency measurement uses mathematical programming and basic assumptions regarding technology to construct a technological frontier representing best practices on the basis of observations on a sample of decision-making units; then, the relative position of each unit in the sample is compared to the frontier in terms of a performance indicator (further details in Cooper et al. 2007).\(^9\) While assumptions about the technology have been already established, the mathematical programme that assesses the proportional GHG eco-efficiency of the EU-27 country $c'$, i.e. the directional distance function of expression (4), is as follows:

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\(^8\) Further scenarios assessing, for instance, potential increases in GDP while maintaining GHG emissions or even increases in GDP at the same time as emissions are reduced can be modelled by the appropriate directional distance functions. However, modelling these scenarios goes beyond the scope of this paper.

\(^9\) In addition, one advantage of DEA techniques over other approaches commonly used to build composite indicators is that the weights assigned to individual GHG emissions in computing the aggregated emission score are determined endogenously (see Cherchye et al. 2007), so no a priori weights based on exogenous information are required, e.g. opinion of experts.
Maximize $\Phi_{c',\lambda} \text{Eco-efficiency}_{c'}^{\lambda} = \Phi_{c'}^{\lambda}$

Subject to:

(i) $g_c' \leq \sum_{c=1}^{27} \lambda_c g_c'$

(ii) $(1 - \Phi_{c'}^{\lambda}) e_i' \geq \sum_{c=1}^{27} \lambda_c e_i' \quad e_i' \in e$ and $e_i' \notin e_i'$

(iii) $e_{-i}' \geq \sum_{c=1}^{27} \lambda_c e_{-i}' \quad e_{-i}' \in e$ and $c = 1, \ldots, 27$

where $\lambda_c$ stands for the weighting of each country $c$ in the composition of the eco-efficient frontier country $c'$ is compared to.

The objective in programme (6) is to find the maximum proportion by which country $c'$ could reduce its GHG emissions without decreasing GDP; furthermore, this target is subject to a series of restrictions. According to restriction (6)-(i), country $c'$ must generate no more GDP than the eco-efficient point on the technological frontier it is projected to. Additionally, restriction (6)-(ii) means that at its projection onto the technological frontier, country $c'$ must emit no less GHGs than the eco-efficient point it is compared to. Finally, restriction (6)-(iii) entails that the countries in the sample cannot enter the technological frontier with a negative weight, also imposing constant returns to scale.

Furthermore, the mathematical programme that assesses eco-efficiency in the direction of a particular GHG emission, i.e. the directional distance function of expression (5), which assesses greenhouse-gas-specific eco-efficiency, is formulated as:

Maximize $\Phi_{e_i',\lambda} \text{Eco-efficiency}_{e_i'}^{\lambda} = \Phi_{e_i'}^{\lambda}$

Subject to:

(i) $g_{e_i'}' \leq \sum_{c=1}^{27} \lambda_c g_{e_i'}'$

(ii) $(1 - \Phi_{e_i'}^{\lambda}) e_i' \geq \sum_{c=1}^{27} \lambda_c e_i' \quad e_i' \in e$ and $e_i' \notin e_i'$

(iii) $e_{-i}' \geq \sum_{c=1}^{27} \lambda_c e_{-i}' \quad e_{-i}' \in e$ and $c = 1, \ldots, 27$

In this case, restriction (7)-(i) plays the same role as constraint (i) in programme (6), restriction (7)-(ii) is analogous to restriction (6)-(ii), although here it only affects the emission of gas $i$ (either CO$_2$, N$_2$O or CH$_4$). In addition, restriction (7)-(iii) means that country $c'$ must emit no less GHGs other than $i$ (denoted by $-i$) than the eco-efficient point on the technological frontier it is compared to; finally, restriction (7)-(iv) assures, once again, that individual countries cannot enter the eco-efficient frontier with a negative weight.

2.3 A brief comment on eco-efficiency

Eco-efficiency for the EU-27 countries during the period 1990–2009 has been computed by running programme (6) for each country and year in the scenario in which all emissions are proportionally reduced, i.e. proportional GHG eco-efficiency, and
programme (7) when reductions of specific emissions are considered, i.e. greenhouse-gas-specific eco-efficiency. Table 3 displays some descriptive statistics of these scores at the beginning and the end of the period, which allow us to implement a comparative static-type exercise. In 2009, proportional GHG eco-efficiency in the EU-27 has a mean value of 0.458. Furthermore, the average scores of greenhouse-gas-specific eco-efficiency in CO₂, N₂O and CH₄ emissions are 0.584, 0.581 and 0.609, respectively, so the highest level of eco-efficiency corresponds to nitrous oxide, while the worst corresponds to the emissions of methane. Furthermore, the countries behaving eco-efficiently, i.e. the countries that shape the technological frontier against which other countries are compared, are Luxembourg, Malta and Sweden. Conversely, the worst eco-efficiency levels clearly correspond to the Central and Eastern European countries that joined the EU in 2004 and 2007, such as Bulgaria, Estonia, Poland or the Czech Republic, among others.

In order to delve deeper into the interpretation of our eco-efficiency scores and their utility to European policymakers, we can take the case of the Czech Republic as an example. In 2009, this country recorded a score of 0.797 in the measure of proportional GHG eco-efficiency. This figure was obtained from the comparison of GDP and GHG emissions in the Czech Republic with a virtual observation located on the eco-efficient frontier¹⁰, and means that emissions of GHGs could be proportionally reduced by nearly 80% while maintaining GDP at its observed level. If we now consider, for instance, the methane greenhouse gas, our results show that emissions in the Czech Republic could be reduced by 88.3% while maintaining GDP and, more importantly, without increasing emissions of carbon dioxide and nitrous oxide. In other words, the specific methane score of eco-efficiency is 0.883.

From the comparison of the values calculated at the beginning and end of the period we can observe that the profile of eco-efficiency in 1990 is similar to that described above for 2009, with some core European countries and some Scandinavian economies among the most eco-efficient countries, whereas the most recent EU members are the least eco-efficient. Furthermore, many countries have improved their relative levels of eco-efficiency, particularly the UK¹¹, while others have recorded worse scores, namely Italy, Cyprus, Spain, Portugal and Slovenia.

It is also worth highlighting the large differences observed in eco-efficiency among EU countries. Several factors may explain this behaviour, including as mentioned in the Introduction, their respective levels of development, differences in the structure

¹⁰ This virtual eco-efficient observation results from a combination of observations on Malta, Luxembourg and Sweden, with weightings 4.676, 0.365 and 0.158, respectively.

¹¹ This important improvement in eco-efficiency in the UK was also found by Kortelainen (2008), who assesses the global eco-efficiency of 20 European Union countries over the period 1990–2003. This study uses data from the European Environmental Agency on the emissions of 12 pollutants representing four different environmental pressure categories, including carbon dioxide, nitrogen oxides and methane, among others. Furthermore, in a comparative analysis of Finland and the UK for the period 1990–2006, Marrero (2010) found that starting from the same 1990 level, and having experienced similar economic growth, by 2006 the UK had lowered its GHG emissions to a much greater extent than Finland. Thus, given that a similar extent of eco-efficiency improvement has also been found by other researchers, it would be interesting to investigate the determinants of this particular behaviour in the UK as a case study; however, this issue goes beyond the scope of this paper.
with other Scandinavian economies has traditionally displayed a high level of environ-

Table 3 Scores of eco-efficiency in greenhouse gas emissions

| Country                  | GHG  | CO₂  | N₂O  | CH₄  | GHG  | CO₂  | N₂O  | CH₄  |
|--------------------------|------|------|------|------|------|------|------|------|
| Austria (Au)             | 0.104| 0.324| 0.151| 0.373| 0.144| 0.476| 0.207| 0.318|
| Belgium (Be)             | 0.313| 0.557| 0.497| 0.351| 0.283| 0.610| 0.429| 0.305|
| Bulgaria (Bu)            | 0.951| 0.951| 0.979| 0.967| 0.907| 0.932| 0.959| 0.962|
| Cyprus (Cy)              | 0.360| 0.583| 0.566| 0.711| 0.439| 0.753| 0.676| 0.798|
| Czech Republic (Cz)      | 0.849| 0.905| 0.917| 0.895| 0.797| 0.892| 0.898| 0.883|
| Denmark (Dk)             | 0.236| 0.337| 0.552| 0.236| 0.343| 0.433| 0.442| 0.482|
| Estonia (Es)             | 0.899| 0.953| 0.943| 0.926| 0.837| 0.907| 0.921| 0.899|
| Finland (Fi)             | 0.445| 0.506| 0.618| 0.451| 0.402| 0.586| 0.580| 0.428|
| France (Fr)              | 0.218| 0.218| 0.554| 0.427| 0.360| 0.360| 0.501| 0.593|
| Germany (De)             | 0.368| 0.583| 0.584| 0.498| 0.271| 0.589| 0.480| 0.293|
| Greece (Gr)              | 0.611| 0.663| 0.817| 0.644| 0.514| 0.740| 0.725| 0.671|
| Hungary (Hu)             | 0.828| 0.828| 0.936| 0.869| 0.795| 0.812| 0.916| 0.880|
| Ireland (Ie)             | 0.577| 0.577| 0.868| 0.875| 0.515| 0.515| 0.678| 0.817|
| Italy (It)               | 0.082| 0.312| 0.142| 0.201| 0.203| 0.567| 0.311| 0.482|
| Latvia (La)              | 0.846| 0.846| 0.949| 0.903| 0.739| 0.739| 0.935| 0.901|
| Lithuania (Li)           | 0.877| 0.877| 0.956| 0.913| 0.785| 0.785| 0.966| 0.917|
| Luxembourg (Lu)          | 0.000| 0.000| 0.000| 0.000| 0.000| 0.000| 0.000| 0.000|
| Malta (Ma)               | 0.000| 0.000| 0.000| 0.000| 0.000| 0.000| 0.000| 0.000|
| Netherlands (Ni)         | 0.441| 0.501| 0.600| 0.615| 0.170| 0.454| 0.277| 0.560|
| Poland (Pl)              | 0.883| 0.910| 0.942| 0.911| 0.811| 0.874| 0.914| 0.881|
| Portugal (Pt)            | 0.369| 0.436| 0.502| 0.700| 0.435| 0.644| 0.629| 0.835|
| Romania (Ro)             | 0.928| 0.928| 0.975| 0.964| 0.894| 0.894| 0.970| 0.963|
| Slovak Republic (Sk)     | 0.800| 0.876| 0.918| 0.800| 0.730| 0.799| 0.883| 0.828|
| Slovenia (Sl)            | 0.535| 0.682| 0.757| 0.737| 0.553| 0.740| 0.783| 0.781|
| Spain (Sp)               | 0.369| 0.450| 0.508| 0.415| 0.414| 0.610| 0.585| 0.663|
| Sweden (Sw)              | 0.000| 0.000| 0.000| 0.000| 0.000| 0.000| 0.000| 0.000|
| United Kingdom (UK)      | 0.333| 0.446| 0.466| 0.635| 0.016| 0.054| 0.024| 0.314|
| Averages                 | 0.298| 0.394| 0.457| 0.428| 0.271| 0.442| 0.391| 0.451|
| European Union-15        | 0.490| 0.565| 0.618| 0.593| 0.458| 0.584| 0.581| 0.609|
| European Union-27        | 0.298| 0.394| 0.457| 0.428| 0.271| 0.442| 0.391| 0.451|

of economic activity (closely related to the level of development) and environmental awareness, among others. In the group of eco-efficient countries, Luxembourg is a highly developed economy and enjoys the largest GDP per capita in the EU-27. It is highly oriented towards service activities and, particularly, banking and financing services; Sweden is also among the most developed European countries and together with other Scandinavian economies has traditionally displayed a high level of environ-
mental awareness; finally, Malta is a small country where tourism and agriculture are the main economic activities. In contrast, the newer EU members are mostly geared towards industrial activities and, moreover, in these countries environmental regulations are more recent than in other Western European countries.

In order to empirically illustrate the relationship between eco-efficiency and the sectoral structure of economic activity, we have computed the Spearman correlation coefficient between our four eco-efficiency indicators, on the one hand, and the percentage share of industrial activities (excluding the building industry) in aggregate value added, on the other. For 2009, the correlations are 0.558, 0.536, 0.518 and 0.467 for proportional GHG eco-efficiency and eco-efficiency in CO₂, N₂O and CH₄ emissions, respectively. Furthermore, all correlations are statistically significant at standard confidence levels (the \( p \)-values are 0.002, 0.003, 0.005 and 0.014, respectively).

The arguments mentioned in the previous paragraphs imply that, given the assessment of eco-efficiency at country level carried out in this research, a literal interpretation of our scores of eco-efficiency, i.e. merely as they have been formulated in the methodological section, could result in misleading conclusions. Instead, their interpretation needs to be qualified much further than their merely analytical formulation. In fact, in order for eco-inefficient countries to approach leading European countries, they should move towards cleaner production processes, increasing environmental awareness and also change their respective production structures towards less contaminating activities. For instance, in order to improve the GHG eco-efficiency of the Czech Republic, which scored 0.797 in 2009, both cleaner practices and changes in its production structure would be required (perhaps by reducing the significance of some highly pollutant activities, such as heavy industry and coal and lignite mining activities). Nevertheless, we believe that beyond the forces that could drive EU countries to improve their respective levels of eco-efficiency, analysing convergence in eco-efficiency is of scientific interest by itself, as already noted by Kortelainen (2008, p. 709). Furthermore, our opinion is that, as mentioned in the Introduction, this analysis has the potential to produce relevant information to help European policymakers to design better environmental policies regarding GHG emissions and climate change.

Thus, the rest of this paper will concentrate on the study of convergence, leaving the

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12 The data on the structure of productive activity come from AMECO, the annual macro-economic database of the European Commission’s Directorate General for Economic and Financial Affairs; they have been accessed on 19th July 2012 through http://ec.europa.eu/economy_finance/db_indicators/ameco.

13 It is worth to highlight here that dozens of papers in the field of efficiency and productivity measurement have addressed the assessment of performance at macro level using aggregate data from regions or countries (Färe et al. 1994; Lovell et al. 1995). Moreover, most of this research is specifically focused on the study of environmental performance (Zofio and Prieto 2001; Zhou et al. 2006, 2007) and even eco-efficiency (Kortelainen 2008).

14 Countries’ production structures are largely determined by their relative endowment of productive resources, as well as the patterns of demand; for instance, large coastlines and favourable climatic conditions have fostered specialisation in tourism in Mediterranean European countries such as Spain. Notwithstanding, trade and increasing foreign direct investment liberalisation might favour the reallocation of polluting activities from industrial countries to developing countries with lower environmental standards (pollution haven hypothesis).
analysis of the factors that explain differences in GHG emissions eco-efficiency for further research.

3 Is eco-efficiency in greenhouse gas emissions converging in the European Union?

3.1 Methodological approach to measure convergence

As has already been discussed in the Introduction, enforcing environmental policies is not always easy. However, in an integrated area such as the European Union, we may find relatively supportive evidence of similar behaviour patterns. Using the concept of convergence in this setting can be too rigid, as the assimilation of cleaner technologies may imply a relatively long process. This is why the econometric methodology that we adopt relies on the concept of convergence clubs. It implies finding groups of countries that converge to more than one reference level. Alternative methodologies have been applied using this less rigid concept, such as the proposal made by Quah (1996) or that put forward by Hobijn and Franses (2000) referring to relative convergence.

In this paper we test for the existence of convergence clubs in eco-efficiency using the methodology in Phillips and Sul (2007). This non-linear, time-varying coefficient factor model has well-defined asymptotic properties. A regression-based test is proposed, together with a clustering procedure. This approach is not dependent on stationarity assumptions and allows for a wide variety of possible transition paths towards convergence (including subgroup convergence). Moreover, the same test is applied for overall convergence and clustering. Factor analysis is an important tool for analysing datasets with large time series and cross section dimensions, as the series can be parsimoniously decomposed into common and country-specific components. It is important, when testing for convergence, to allow for some degree of heterogeneity. In the case of the foregoing authors, they capture heterogeneous behaviour using an empirical model based on a common factor structure and idiosyncratic effects. They start with a simple single factor model, such as:

\[ X_{it} = \delta_i \mu_t + \varepsilon_{it} \]  

where \( \delta_i \) measures the idiosyncratic distance between the common factor \( \mu_t \) and the systematic part of \( X_{it} \). \( \mu_t \) may have different interpretations, either representing the aggregated common behaviour of \( X_{it} \) or any common variable that may influence individual economic behaviour. This model seeks to capture the evolution of the elements of \( X_{it} \) in relation to \( \mu_t \) using two idiosyncratic elements: a systematic one \( (\delta_i) \) and an error one \( (\varepsilon_{it}) \).

Phillips and Sul (2007) make two contributions to this simple model. First, they extend Eq. (8) by allowing the systematic idiosyncratic element to evolve over time (aiming to accommodate the heterogeneous evolution of agents). They also allow \( \delta_{it} \) to have a random component, which absorbs \( \varepsilon_{it} \) and permits possible convergence behaviour in \( \delta_{it} \) over time in relation to the common factor \( \mu_t \). In this case, the new model has a time varying factor representation:
Thus, the model accounts for special behaviour in the idiosyncratic element \( \delta_{it} \) which they model in semiparametric form. A non-stationary transitional behaviour of factor loadings is assumed, such that each coefficient converges to a unit specific constant:

\[
\delta_{it} = \delta_i + \sigma_i \xi_{it} L(t)^{-1} t^{-\alpha}
\]

where \( \delta_i \) is fixed, \( \xi_{it} \sim \text{iid}(0, 1) \) across \( i \) but weakly dependent on \( t \) and \( L(t) \) is a slowly varying function (like \( \log t \)) for which \( L(t) \to \infty \) as \( t \to \infty \). This formulation ensures that \( \delta_{it} \) converges to \( \delta_i \) for all \( \alpha \geq 0 \) (the null hypothesis of interest). The parameter of interest is \( \delta_{it} \) and the focus is on its temporal evolution and convergence behaviour.

The second contribution that Phillips and Sul (2007) make is that this setting makes it possible to develop an econometric test of convergence for the time varying idiosyncratic components. Using a simple regression, the hypothesis to test is:

\[
H_0: \delta_{it} \to \delta_i \text{ for some } \delta \text{ as } t \to \infty
\]

Some characteristics make it very useful in applied work: first, the test does not rely on any particular assumption concerning trend stationarity or stochastic nonstationarity in \( X_{it} \) or \( \mu_t \); second, the nonlinear form of (9) is sufficiently general to include many possible time paths for \( \delta_{it} \) and their heterogeneity over \( i \), e.g. it allows for transitionally divergent individual behaviour.

From an economic point of view, \( \delta_{it} \) measures the relative share in \( \mu_t \) (a common trend component in the panel) of individual \( i \) at time \( t \). Thus, \( \delta_{it} \) is a form of individual economic distance between the common trend component \( \mu_t \) and \( X_{it} \). \( \mu_t \) trending behaviour dominates the transitory component. In this context, it is possible to test for convergence by assessing whether the factor loadings \( \delta_{it} \) converge. The central issue of the proposed approach is the estimation of the time-varying loadings \( \delta_{it} \). For this purpose, Phillips and Sul (2007) define the relative transition parameter \( h_{it} \) as:

\[
h_{it} = \frac{X_{it}}{\frac{1}{N} \sum_{i=1}^{N} X_{it}} = \frac{\delta_{it}}{\frac{1}{N} \sum_{i=1}^{N} \delta_{it}}
\]

which measures the loading coefficient \( \delta_{it} \) in relation to the panel average at time \( t \). Phillips and Sul (2007) assume that the panel average and its limit as \( N \to \infty \) differ from zero. The cross-sectional mean of \( h_{it} \) is unity by definition. Moreover, if the factor loading coefficients converge to \( \delta \), the relative transition parameters \( h_{it} \) converge to unity. Then, in the long run, the cross-sectional variance of \( h_{it} \) converges to zero.

Next, Phillips and Sul (2007) construct the cross-sectional mean square transition differential \( H_1/H_t \) where:
Is eco-efficiency in greenhouse gas emissions converging among European Union countries?

\[ H_t = \frac{1}{N} \sum_{i=1}^{N} (h_{it} - 1)^2 \]  \hspace{1cm} (13)

which measures the distance of the panel from the common limit. Using a semiparametric model for \( \delta_{it} \) they obtain:

\[ \delta_{it} = \delta_i + \frac{\sigma_i \xi_{it}}{L(t)t^\alpha} \]  \hspace{1cm} (14)

where \( \xi_{it} \sim iid(0, 1) \) across \( i \), \( L(t) \) is a slowly varying function (such as \( \log t \)) and \( \alpha \) denotes the speed of convergence. Thus, \( \delta_{it} \) converges to \( \delta_i \) for all positive values of \( \alpha \) or when this parameter is zero. The null hypothesis is:

\[ H_0 : \delta_i = \delta \text{ and } \alpha \geq 0 \]  \hspace{1cm} (15)

and the alternative:

\[ H_A : \delta_i \neq \delta \text{ for some } i \text{ and/or } \alpha < 0 \]  \hspace{1cm} (16)

The null hypothesis is tested using the following log \( t \) regression:

\[ \log(H_1/H_t) - 2\log L(t) = \hat{c} + \hat{b} \log t + u_t \]  \hspace{1cm} (17)

where \( L(t) = \log(t + 1) \).

The coefficient of \( \log t \) is \( \hat{b} = 2\hat{\alpha} \), where \( \hat{\alpha} \) is the estimate of the convergence speed \( \alpha \) in \( H_0 \). Using the \( t \)-statistic \( t_b \), the null hypothesis of convergence is rejected when \( t_b < -1.65 \). In empirical analysis, the practice is to remove part of the sample. Phillips and Sul (2007) recommend starting the regression at point \( t = [rT] \), where \( [rT] \) is the integer part of \( rt \) and \( r = 0.3 \). The choice of the subsample to be discarded plays an important role, because both the limit distribution and the power properties of the procedure depend on it.

In the empirical application of the log \( t \) statistic to test for convergence, Phillips and Sul (2007) suggest using a **club convergence algorithm**. The algorithm is based on the logarithmic regression (17) and consists of four steps, which are repeated until all units are sorted into cluster formations and can be summarised as follows:

1. **Step 1 (Ordering):** Order the panel members according to the last observation. This provides a first reference for the configuration of the groups. In cases of high volatility, the ordering can be done according to the average.
2. **Step 2 (Core group formation):** Once the members have been ordered, we calculate the convergence \( t \)-statistic, \( t_k \), and select the \( k \) highest members with \( 2 \leq k \leq N \). The size of the group is determined based on the maximum \( t_k \) with \( t_k > -1.65 \).
3. **Step 3 (Club membership):** Selection of the members of the core group (Step 2) by adding one at a time. A new country is included if the associated \( t \)-statistic is greater than zero. Then the \( t \) test is run with the first sub-convergence group to ensure that \( t_k > -1.65 \) for the whole group.
4. The non-selected countries in Step 3 form a complementary group. Then the log \( t \) regression is applied to this set of countries. If they converge, they form a second convergence club. If not, Steps 1 to 3 are repeated to detect sub-convergence clusters. If no core group is found in Step 2, the patterns displayed by these countries are divergent.

The procedure possesses great flexibility that enables one to identify cluster formations with all the possible configurations: overall convergence, overall divergence, converging subgroups and single diverging units.

3.2 Results for convergence and discussion

In this Section we discuss the main results on eco-efficiency convergence in emissions of pollutants that cause greenhouse effects. As highlighted in the Introduction, there is extensive literature that provides evidence of convergence, mainly in CO\(_2\) emissions, for different sets of industrialised countries; the papers by Jobert et al. (2010) and Marrero (2010), which show evidence on the existence of conditional convergence in terms of GHG emissions among the EU27, are of particular interest for the purpose of our research.

As Schmalensee et al. (1998) indicated, high-income countries, such as Germany, France, Sweden, the Netherlands and the UK have started to reduce per capita GHG emissions, while others in the same area, such Spain, Portugal and Italy have increased emissions over the period analysed in their study. Moreover, some Eastern European countries, such as the Czech Republic, Hungary, Poland and Slovakia, have reduced GHG emissions even more than the richest EU countries. The literature on growth and convergence (Barro and Sala-i-Martin 1992) has recently been applied to explain the evolution of emissions. According to this theory, countries with higher initial levels of emissions tend to reduce emissions more than countries with lower initial levels. That would explain the substantial drop in the emissions in Eastern European countries, despite having smaller per capita GDP. However, this theory is not able to explain the case of Spain, Greece or Ireland, whose emissions growth is clearly above that associated to their 1990 levels. Some authors have stressed differing economic growth rates as an explanatory variable for this heterogeneous behaviour. However, there are still cases that cannot be explained even by this dual growth-convergence relationship.\(^{15}\) Therefore, the relationship between growth and GHG emissions can be best analysed by eco-efficiency indicators. The dynamics of these indicators points to the existence of other factors, such as technological change and energy mix variations, which could help to explain the change in emissions between 1990 and 2009 in Europe.

Although the group of countries that we analyse is relatively homogeneous and subject to common policies and laws, EU countries exhibit heterogeneous characteristics associated to their differences in income and level of development. Moreover, many of its members (the Central and Eastern European countries together with the Baltic

\(^{15}\) As previously noted, Marrero (2010) singles out the comparative case of the UK and Finland. Even though both economies recorded similar emission levels in 1990 and had a comparable growth rate over the sample period analysed (1990–2006), the UK lowered its emissions to a much greater extent than Finland.
Table 4  Convergence Club classification: eco-efficiency of emissions

| GHG emissions | CO₂emissions | N₂O emissions | CH₄emissions |
|---------------|--------------|---------------|--------------|
| Club 1        | Club 1       | Club 1        | Club 1       |
| [Lu, Ma, Sw, UK] | [Lu, Ma, Sw, UK] | [Lu, Ma, Ni, Sw, UK] | [Be, De, Lu, Ma, Sw, UK] |
| logₜ t-stat    | logₜ t-stat  | logₜ t-stat   | logₜ t-stat  |
| 6.03          | 3.90         | 2.42          | 7.55         |
| Club 2        | Club 2       | Club 2        | Club 2       |
| [Au, Be, Dk, Fi, Fr, De, It, Ni] | [Dk, Fr, Ie, La] | [Au, Be, Dk, Fi, Fr, De, Ie, It] | [Au, Dk, Fi] |
| logₜ t-stat    | logₜ t-stat  | logₜ t-stat   | logₜ t-stat  |
| 0.14          | 2.96         | 0.12          | 1.99         |
| Club 3        | Club 3       | Club 3        | Club 3       |
| [Cy, Gr, Ie, La, Pr, Sl, Sp] | [Au, Be, Fi, De, It, Li, Ni] | [Cy, Es, Gr, Pr, Sl, Sp] | [Fr, Gr, It, Nl] |
| logₜ t-stat    | logₜ t-stat  | logₜ t-stat   | logₜ t-stat  |
| 0.29          | 4.83         | 0.27          | 3.83         |
| Club 4        | Club 4       | Club 4        | Club 4       |
| [Es, Li, Sk]  | [Bu, Cy, Cz, Es, Gr, Hu, Pl, Pr, Ro, Sk, Sl, Sp] | [Cz, Hu, La, Pl, Sk] | [Cy, Cz, Es, Hu, Ie, La, Li, Pl, Pr, Sk, Sl, Sp] |
| logₜ t-stat    | logₜ t-stat  | logₜ t-stat   | logₜ t-stat  |
| 0.26          | 12.69        | −0.083        | −1.35        |
| Club 5        | Club 5       | Club 5        | Club 5       |
| [Cz, Hu, Pl]  | [Bu, Li, Ro] | [Bu, Ro]      |              |
| logₜ t-stat    | logₜ t-stat  | logₜ t-stat   | logₜ t-stat  |
| 0.43          | 25.64        | 0.57          | 9.81         |
| Club 6        |              |              |              |
| [Bu, Ro]      |              |              |              |
| logₜ t-stat    |              |              |              |
| 1.58          | 10.13        |              |              |

* denotes rejection

republics) joined the EU much later and their economic systems were not adapted to international market competition. Therefore, the adoption of cleaner technologies has evolved at different paces among them. In this Section we present the results of the application of the Phillips and Sul (2007) club convergence methodology in Table 4. The first column reports the results for total emissions, while each of the rest of the columns refer to specific pollutants on an individual basis. As already described in Sect. 3.1 above, these results have been obtained from the application of the club convergence algorithm. The main hypothesis is that the countries form a converge club. If the value of the $t$-statistic is greater than $1.65$, there is convergence among this group.

The first column includes the results for the measure of proportional GHG eco-efficiency in which all pollutants are reduced. The first club, which corresponds to the best performers, consists of the three that were on the efficiency frontier (Luxemburg,
Malta and Sweden) and the UK. A second group includes some of the richest European economies: Austria, Belgium, Denmark, Finland, France, Germany, Italy and the Netherlands. The next group consists of Cyprus, Greece, Ireland, Latvia, Portugal, Slovenia and Spain, most of which are peripheral countries or more dynamic recent members, such as Slovenia and Latvia. Former communist countries and two Baltic republics make up the final three groups (clubs 4, 5 and 6). All the UE-27 countries analysed are included in a club, so not one lies outside the different clubs (groups) formed by the algorithm. The $t$-statistic of the sixth group is also larger than the critical value and, therefore, Bulgaria and Romania (the countries displaying the worst performance) also form a club.

The clubs obtained for eco-efficiency in CO$_2$ emissions are reported in the second column and are quite similar to the aggregate case, although the number of clubs is smaller: only four in this case. The first group consists of the same countries, the best performers and the UK. A second club includes Denmark, France, Ireland and Latvia, whereas the third is formed by Austria, Belgium, Finland, Germany, Italy, Lithuania and the Netherlands. Finally, the fourth club includes the 12 remaining countries, among them Greece, Spain and Portugal.

A similar pattern is displayed in N$_2$O and CH$_4$ emissions, the third and fourth columns, respectively, where we find five clubs for each case. Although the individual members of each club are not the same, there are many coincidences and common patterns similar to the two previous variables. The first club also includes the Netherlands in the case of N$_2$O emission eco-efficiency, whereas Belgium, Germany and the four best performers are those included in club 1 for CH$_4$ emissions. The second and third clubs consist of core European countries (Austria, Denmark, France and Italy), whereas Southern European countries and the newest additions to the EU are those that compose the fourth and fifth clubs.

Next, we applied the Phillips and Sul (2009) test for club merging. The main purpose of this testing procedure is to ascertain whether some of the clubs already identified by the convergence club algorithm can be merged, so that the final number of clubs is reduced. We have tested for several group formations, concluding that none of them can be merged, so we should maintain the original club classification.

Further information concerning the dynamics of convergence clubs can be obtained from the graphs of the relative transition paths that are shown in Fig. 1. To simplify the analysis we present the average transition path of each club instead of individual-country performance. The transition paths represent the evolution of each convergence club relative to the average. We should note that the best performing groups appear in the upper part of the graph, whereas those lagging behind are in the lower part.

As for the measure of GHG emission eco-efficiency, we can observe that the first club (which includes the best performers) has a positive slope, i.e. it converges towards higher levels of eco-efficiency. Although the second group is also above the average, the slope is negative. The rest of the groups are below one, but most of them are slowly improving. The only exception is club 3 (including Southern or peripheral European countries), which remains close to one but is not improving.

16 Despite the algorithm finding 5 clubs in the case of N$_2$O, in club 4 the hypothesis of convergence must be rejected. Thus, these countries do not converge and, in fact, there are just 4 groups.
In the next graphs we report the breakdown by pollutant. Concerning CO$_2$ eco-efficiency, the first club consists of the four best performers and has a clearly positive slope. In the case of clubs 2 and 3 below, some of the countries display an upward trend, but the majority worsen. This explains the almost flat evolution of the groups and, on average, a downward trend in clubs 3 and 4. The third and fourth figures correspond to eco-efficiency convergence in N$_2$O and CH$_4$ emissions, respectively. Both graphs are very similar and confirm the evidence found for CO$_2$ and the overall measure of
N$_2$O emissions eco-efficiency

CH$_4$ emissions eco-efficiency

Fig. 1 continued

GHG eco-efficiency: the best performers (Luxemburg, Malta, Netherlands, Sweden and the UK) form a consistent and continuously improving group, whereas the rest of the countries and groups are relatively stuck and progress very slowly towards the average.

The policy implications of these findings should be considered tentative, as the country-classification obtained is not homogeneous for all the pollutants considered. Concerning the measure of GHG proportional eco-efficiency, the main policy conclu-
sion is that the core European countries as well as the most advanced peripheral and former communist countries are converging towards the average. Looking at particular pollutants, the worst general outcomes are obtained in the case of CO₂, for which many countries are in reality converging well below the average. These results may indicate that catching up and growth has clearly had negative effects on the environment and that European environmental policy should apply more stringent principles to member countries, especially those where traditional industries in mature sectors may still be using highly pollutant technologies.

Furthermore, our results are in line with the European Environmental Agency (EEA) (2012) report on greenhouse gas emission. Although we are studying an indicator of eco-efficiency and not emissions, some of our conclusions reflect each country’s relative performance in relation to the Kyoto protocol. The EU-15 has a common target to be achieved collectively, although the agreement sets differentiated emission limitation and reduction targets for each member country. In this group, only Italy is not on track, while authorities in Spain have decided to acquire a large quantity of Kyoto units using other mechanisms. This joint EU-15 behaviour is reflected in the general indicator that shows a tendency in core EU countries to converge towards the average. Spain and Italy are usually underperformers, which maybe due to their difficulties to reach the target. Post-2004 EU members have only individual targets, which might explain why many of them form separate groups.

The conclusions of the above-mentioned European Environmental Agency (EEA) (2012) report are rather discouraging: although the short-term Kyoto targets may be reached, a stronger effort should be made to sustain the progress achieved and to fulfil medium to long-term targets. The slow progress or even the worsening of some of the convergence patterns in our eco-efficiency results also point to these difficulties.

4 Concluding remarks

This paper contributes to the previous literature on GHG emissions convergence in two respects. First, we refine the definition of the variable analysed by constructing an indicator of eco-efficiency for both aggregate GHG emissions and for each of the most important individual pollutants included in this class of gases, namely, carbon dioxide, nitrous oxide and methane. Second, the methodological approach that we follow to measure convergence allows us to classify countries in a flexible way into convergence clubs. This approach is especially suited to environmental variables where the classical concepts of convergence (absolute or conditional) may be too rigid to be fulfilled. Moreover, this methodology allows us to measure the dynamics of the convergence process and accounts for cross section dependence in a common factor model framework.

To sum up, our results are compatible with previous studies that analyse GHG emissions convergence within European Union countries for similar sample periods using rough indicators. The eco-efficiency analysis shows along the whole period studied that countries behaving eco-efficiently, i.e. the countries shaping the technological frontier against which other countries are compared, are Luxembourg, Malta and Sweden. Conversely, the worst eco-efficiency levels are clearly recorded by the
Central and Eastern European countries that joined the European Union in 2004 and 2007. From a dynamic point of view, the results found point to the existence of four to six convergence clubs depending on the specific pollutant. The first club is generally formed by Luxembourg, Malta and Sweden together with the UK. A second club including countries with similar characteristics is composed of core European Union countries, like Germany, Austria, Belgium, France, Italy, Denmark and Finland. Moreover, a third club is made up of peripheral countries, such as Spain, Greece, Cyprus and Portugal, together with Latvia and Slovenia. All of them have notably increased their emissions and, therefore, have witnessed a worsening in eco-efficiency.

One possible explanation for this differing evolution across countries in the two first clubs on the one hand, and the third club on the other, could be the difference in initial income levels among the countries belonging to the different clubs. However, this relationship between emissions and initial income levels disappears when we analyse the performance of the Eastern European countries included in the rest of the convergence clubs, which have improved greatly in eco-efficiency terms. This fact reveals the existence of other factors, such as technological improvements or energy-mix changes, which might help to explain the heterogeneous evolution of eco-efficiency in the European Union to date. Therefore, although the European Union seems to be progressing in the right direction and a convergence in programmes and policies against climate change is being achieved among its members, more effort in regulatory aspects is still required to achieve dynamic convergence in eco-efficiency.

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References

Albrecht J, Arts B (2005) Climate policy convergence in Europe: an assessment based on National Communications to the UNFCCC. J Eur Public Policy 12:885–902
Aldy J (2006) Per capita carbon dioxide emissions: convergence or divergence? Environ Resour Econ 33(4):533–555
Aldy J (2007) Divergence in state-level per capita carbon dioxide emissions. Land Econ 83:353–369
Barassi MR, Cole MA, Elliott RJR (2008) Stochastic divergence or convergence of per capita carbon dioxide emissions: re-examining the evidence. Environ Resour Econ 40:121–137
Barassi MR, Cole MA, Elliott RJR (2011) The stochastic convergence of CO2 emissions: a long memory approach. Environ Resour Econ 49:367–385
Barro R, Sala-i-Martin X (1992) Convergence. J Politic Econ 100:223–251
Camarero M, Picazo-Tadeo AJ, Tamarit C (2008) Is the environmental performance of industrialized countries converging? A ‘SURE’ approach to testing for convergence. Ecol Econ 66:653–661
Camarero M, Castillo J, Picazo-Tadeo AJ, Tamarit C (2013) Eco-efficiency and convergence in OECD countries. Environ Resour Econ 55:87–106
CEC (1993) Towards sustainability: a European Community Programme of policy and action in relation to the environment and sustainable development. Office for Official Publications of the European Communities, Luxembourg
Chambers RG, Chung Y, Färe R (1998) Profit, directional distance functions and Nerlovian efficiency. J Optim Theory Appl 98:351–364
Charnes A, Cooper WW, Rhodes E (1978) Measuring the efficiency of decision making units. Eur J Oper Res 2:429–444
Cherchye L, Moesen W, Rogge N, van Puyenbroek T (2007) An introduction to ‘benefit of the doubt’ composite indicators. Soc Indic Res 82:111–145
Cooper WW, Seiford LM, Tone K (2007) Data Envelopment Analysis. A comprehensive text with models, applications, references and DEA-Solver software. Springer, New York
European Environmental Agency (EEA) (2012) Greenhouse gas emissions trends and projections in Europe 2012. Tracking progress towards Kyoto and 2020 targets. Technical report No 6/2012.
European Environmental Agency (EEA) (2011) Annual European Union greenhouse gas inventory 1990–2009 and inventory report 2011. Technical report No 2/2011.
Ezcurra R (2007) Is there cross-country convergence in carbon dioxide emissions? Energ Policy 35:1363–1372
Färe R, Grosskopf S (2000) Theory and application of directional distance functions. J Prod Anal 13:93–103
Färe R, Grosskopf S, Norris M, Zhang Z (1994) Productivity growth, technical progress and efficiency change in industrialized countries. Am Econ Rev 84:66–83
Hobijn B, Franses PH (2000) Asymptotically perfect and relative convergence of productivity. J Appl Econom 15:59–81
Huppes G, Ishikawa M (2005) A framework for quantified eco-efficiency analysis. J Ind Ecol 9:25–41
International Energy Agency (IEA) (2011) World energy outlook 2011. Paris.
International Panel for Climate Change (IPCC) (2007) In: Solomon S et al (eds) Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge
Jobert Th, Karkanfil F, Tykronen A (2010) Convergence of per capita carbon dioxide emissions in the EU: legend or reality? Energ Econ 32(6):1364–1373
Kortelainen M (2008) Dynamic environmental performance analysis: a Malmquist index approach. Ecol Econ 64:701–715
Kuosmanen T, Kortelainen M (2005) Measuring eco-efficiency of production with Data Envelopment Analysis. J Ind Ecol 9:59–72
Lanne M, Liski M (2004) Trends and breaks in per-capita carbon dioxide emissions, 1870–2028. Energ J 25:41–65
Lovell CAK, Pastor JT, Turner JA (1995) Measuring macroeconomic performance in the OECD: a comparison of European and non-European countries. Eur J Oper Res 87:507–518
Marrero G (2010) Greenhouse gases emissions, growth and the energy mix in Europe. Energ Econ 32:1356–1363
Nourry M (2009) Re-examining the empirical evidence for stochastic convergence of two air pollutants with a pair-wise approach. Environ Resour Econ 44:555–570
Ordás Criado C, Grether JM (2011) Convergence in per capita CO2 emissions: a robust distributional approach. Resour Energy Econ 33:637–665
Panopoulou E, Pantelidis T (2009) Club convergence in carbon dioxide emissions. Environ Resour Econ 44:47–70
Phillips PCB, Sul D (2007) Transition modeling and econometric convergence tests. Econometrica 75(6):1771–1855
Phillips PCB, Sul D (2009) Economic transition and growth. J Appl Econom 24:1153–1185
Picazo-Tadeo AJ, Beltrán-Esteve M, Gómez-Limón JA (2012) Assessing eco-efficiency with directional distance functions. Eur J Oper Res 220:798–809
Picazo-Tadeo AJ, Reig-Martínez E, Gómez-Limón JA (2011) Assessing farming eco-efficiency: a Data Envelopment Analysis approach. J Environ Manage 92:1154–1164
Picazo-Tadeo AJ, Reig-Martínez E, Hernández-Sancho F (2005) Directional distance functions and environmental regulation. Resour Energy Econ 27:131–142
Quah D (1996) Twin peaks: growth and convergence in models of distribution dynamics. Econ J 106(437):1045–1055
Romero-Avila D (2008) Convergence in carbon dioxide emissions among industrialized countries revisited. Energ Econ 30:2265–2282
Schmalensee RT, Stoker M, Judson RA (1998) World carbon dioxide emissions: 1950–2050. Rev Econ Stat 80:1:15–27
Schmidheiny S, Zorraquin FJL (1996) Financing change, the financial community, eco-efficiency and sustainable development. MIT Press, Cambridge
Strazicich MC, List JA (2003) Are CO2 emission levels converging among industrial countries? Environ Resour Econ 24:263–271
United Nations (2009) Eco-efficiency indicators: Measuring resource-use efficiency and the impact of economic activities on the environment. Greening of Economic Growth Series, ST/ESCAP/2561.

Westerlund J, Basher SA (2008) Testing for convergence in carbon dioxide emissions using a century of panel data. Environ Resour Econ 40:109–120

Zhou P, Poh KL, Ang BW (2007) A non-radial DEA approach to measuring environmental performance. Eur J Oper Res 178:1–9

Zofio JL, Prieto AM (2001) Environmental efficiency and regulatory standards: The case of CO2 emissions from OECD industries. Resour Energy Econ 23:63–83

Zhou P, Ang BW, Poh KL (2006) Slacks-based efficiency measures for modeling environmental performance. Ecol Econ 60:111–118