estructuraeconòmica
ECONOMÍA APLICADA II

A dynamic approach to measuring ecological-economic performance with directional distance functions: greenhouse gas emissions in the European Union

by

Andrés J. Picazo-Tadeo
Juana Castillo
and
Mercedes Beltrán-Esteve

January 2013

Working Papers in Applied Economics

WPAE-2013-04

ECONOMÍA APLICADA II

VNIVERSITAT DE VALÈNCIA

Departamento de Estructura Económica (Economía Aplicada II), Facultad de Economía, Universitat de València
Avda dels Tarongers, s/n, 46022 – Valencia, Spain
Phone +34 96 382 83 49 / Fax +34 96 382 83 54
http://www.estructuraeconomica.es
e-mail: investigacion.estructura@uv.es

ISSN 2172-3036

A dynamic approach to measuring ecological-economic performance with directional distance functions: greenhouse gas emissions in the European Union

Andrés J. Picazo-Tadeo*, Juana Castillo and Mercedes Beltrán-Esteve

Departamento de Economía Aplicada II. Universidad de Valencia.
Campus de Tarongers. 46022, Valencia. Spain.

* Corresponding author. Email: andres.j.picazo@uv.es

ABSTRACT. The impact of economic activity on the environment is a matter of growing concern for firm managers, policymakers, researchers and society as a whole. Building on previous work by Kortelainen [Kortelainen, M., 2008. Dynamic environmental performance analysis: A Malmquist index approach. Ecological Economics 64, 701-715], we contribute an approach to assessing *dynamic ecological-economic performance*, or simply *dynamic eco-performance*, and its two determinants, *ecological-economic efficiency change* and *technical change*, at specific-environmental-pressure level. In doing so, we use *Data Envelopment Analysis* techniques, directional distance functions and *Luenberger* indices. Our approach is employed to assess dynamic eco-performance in the emission of greenhouse gases in the European Union-27 over the period 1990-2010. The main result is that eco-performance has been boosted by technical change rather than by increases in eco-efficiency. Accordingly, policy measures aimed at enhancing eco-efficiency are recommended to improve eco-performance in European countries regarding greenhouse gas emissions.

KEYWORDS: Dynamic eco-performance; directional distance functions; Data Envelopment Analysis; greenhouse gases emissions; European Union.

JEL CLASSIFICATION: C61; O44; Q01; Q54.

1. Introduction

The traditional view of economic growth entirely focused on increasing the quantity of goods and services available to satisfy human needs has given way in recent decades to a vision of growth based on *sustainable development*, understood as the '*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*' (WCED 1987:43). Sustainability is intrinsically a multifaceted concept, which involves at least two strongly related dimensions, namely, the economic dimension and the environmental dimension. The environment contributes to obtaining goods and services, but is also directly affected by economic activity. Production processes influence the quality of the environment due to the use they make of natural resources and the waste they generate. Likewise, availability of natural resources and the restrictions on emissions imposed by environmental regulations affect key economic aspects, such as business profitability.

Literature in the field of ecological economics has long recognised the need to develop tools to assess the impact of productive activity on the environment, as a necessary condition for environmental policies aimed at achieving sustainable development to be effective (Huppes and Ishikawa 2005a; 2009). Accordingly, various approaches have been developed to obtain indicators of the contribution made by products or firms to sustainability, including the *Life Cycle Accounting* and the *Life Cost Cycle*. However, one of the drawbacks of these approaches is that they provide indicators that are difficult to aggregate. Issues such as weighting environmental pressures when building an aggregate indicator of ecological performance, or how to combine ecological and economic performance, are significant problems and at the same time difficult to solve, in that pressures on the environment have no market prices.

As an alternative to using monetary values to solve the incommensurability of environmental pressures, relative measures based on the concept of *ecological-economic efficiency*, or just *eco-efficiency*, and *Data Envelopment Analysis* techniques (DEA) can be employed. According to the OECD (1998:7), '*Eco-efficiency expresses the efficiency with which ecological resources are used to meet human needs* (...) *and can also be defined as a ratio of output and input so that the output represents the value of the products or services that a company produces and the input is the sum of environmental pressures caused by the production*'. Eco-efficiency can be thus understood as a relationship between the economic value generated by a production unit (firm, industry or economy) and an aggregate measure of the pressure exerted on the environment (Schaltegger and Synnestvedt 2002). In addition, several international organisations have recognised that eco-efficiency assessment is a powerful instrument capable of providing managers and policy-makers with helpful information to design better managerial strategies and environmental policies (United Nations 2009).

In this line of research, Kuosmanen and Kortelainen (2005) developed a general framework to measure *relative eco-efficiency* using DEA in a static setting, which Kortelainen (2008) generalised to a dynamic setting. In doing so, professor Kortelainen used *Malmquist* indices (Malmquist 1953) to develop an overall proportional measure of what he called *dynamic envi-*

ronmental performance, which was decomposed into the result of *relative eco-efficiency change* and *environmental technical change*. Our paper extends the approach by Kortelainen (2008) to assessing dynamic eco-performance and its determinants at specific-environmental-pressure level. In doing so, we use *Luenberger* indices (Chambers et al. 1996), directional distance functions and the DEA-based approach to eco-efficiency measurement by Picazo-Tadeo et al. (2012), which assesses eco-efficiency under different scenarios representing the preferences of researchers and/or policymakers regarding economic and ecological performance.

This approach is employed to assess dynamic eco-performance in greenhouse gas (GHG) emissions in the European Union-27 (EU-27) over the period 1990-2010. Global warming and climate change have become a matter of increasing concern for policymakers, researchers and society as a whole in recent decades; in fact, policies combating climate change constitute a cornerstone of current environmental policy in developed countries. Furthermore, researchers generally seem to agree that changes are unequivocal and caused by increasing concentrations of GHG due to human activities, mostly the production and use of energy. Accordingly, our assessment of dynamic eco-performance could provide European policymakers with sound information helping them to design better environmental policies to combat climate change.

Following this Introduction, Section 2 develops the methodology and Section 3 describes the data and the empirical application. Section 4 discusses the results and highlights some policy recommendations, while a final Section concludes and suggests some avenues for future research.

2. Methodology

2.1. Eco-performance, eco-efficiency and technical change

Let us start by assuming that we observe a set of k=1,…,K decision-making units (DMU) which each year from a period t=1,…,T generate an economic result represented by value added v^t. Furthermore, economic activity exerts a series of n=1,…,N damaging pressures on the environment, which in period t are denoted by the vector $\mathbf{p}^t = \left(p_1^t,\ldots,p_n^t\right)$.[1]

The *Pressure Generating Technology Set* (PGTS), which represents all feasible combinations of value added and environmental pressures in period t, is defined as (Kuosmanen and Kortelainen 2005; also see Picazo-Tadeo et al. 2011):

$$\text{PGTS}^t = \left[\left(v^t,\mathbf{p}^t\right) \in R_+^{N+1} \,\middle|\, \text{value added } v^t \text{ can be obtained with pressures } \mathbf{p}^t\right] \tag{1}$$

Technology can also be represented by the *Pressure Requirement Set* (PRS) as defined in Beltrán-Esteve et al. (2012), which represents all the combinations of environmental pressures **p** that permit obtaining at least value added v, and which in period t is defined as:

$$\text{PRS}^t\left(v^t\right) = \left[\mathbf{p}^t \,\middle|\, \left(v^t,\mathbf{p}^t\right) \in \text{PGTS}^t\right] \tag{2}$$

Following Picazo-Tadeo et al. (2012), we assume that technology has the following properties: a) economic activity unavoidably exerts some pressures on the environment, and the only way not to generate pressures is not to produce; b) lower value added can always be obtained exerting the same amount of pressures on the environment; c) pressures on the environment can always be increased for any given value added; and, finally, d) any convex combination of two or more feasible (observed) pairs of value added and environmental pressures is also feasible. In accordance with earlier papers by Korhonen and Luptacik (2004), Kuosmanen and Kortelainen (2005) and Zhang et al. (2008), in this characterisation of the technology environmental pressures are formally treated as conventional inputs.[2]

Let us now define *ecological-economic performance*, or simply *eco-performance*, as the ratio between economic value added and a composite indicator of the aggregate pressure exerted on

[1] Vectors are in bold type throughout the paper to distinguish them from scalars.

[2] Dyckhoff and Allen (2001) discuss different approaches to treating the undesirable results of production processes in DEA-based models.

the environment (Kortelainen 2008). Accordingly, eco-performance would improve when the value added increases with respect to the aggregate environmental pressure. Formally, eco-performance in period t is formulated as:

$$\text{Eco}-\text{performance}^t = \frac{\text{Economic value added}^t}{\text{Aggregate environmental pressure}^t} = \frac{v^t}{w_1 p_1^t + w_2 p_2^t + \ldots + w_n p_n^t} \quad (3)$$

In the computation of the aggregate environmental pressure score we follow the most common approach in literature consisting of taking as aggregating function a linear weighted average of the particular environmental pressures, w_n being the weight awarded to pressure n.

Furthermore, it is worth highlighting that here we interpret the ratio between economic value added and the aggregate pressure in a slightly different manner than Kuosmanen and Kortelainen (2005), where this ratio was used as a measure of *relative ecological-economic efficiency*. The reason is that, for the purpose of our paper, we want to unmistakable separate the concept of eco-efficiency, which involves a relative evaluation of performance with respect to a benchmark, from eco-performance which does not involve such comparison. Other papers have referred to this ratio as *environmental productivity* (Huppes and Ishikawa 2005b).

Our next methodological building block is the *directional distance function* (Färe and Grosskopf 2000)[3] defined in period t as:

$$\vec{D}^t\left[v^t, \mathbf{p}^t; \mathbf{g} = \left(g_v, -\mathbf{g_p}\right)\right] = \text{Sup}\left[\beta \,\middle|\, \left(\mathbf{p}^t - \beta \mathbf{g_p}\right) \in PRS^t\left(v^t + \beta g_v\right)\right] \quad (4)$$

$\mathbf{g} = \left(g_v, -\mathbf{g_p}\right)$ being the so-called direction vector.

The directional distance function provides a complete representation of the PGTS and is lower bounded to zero (other properties are in Chambers et al. 1998). Furthermore, it is a flexible and powerful tool for measuring eco-efficiency, which in turn makes it possible to assess potential increases in economic value added and/or reductions in environmental pressures

[3] Picazo-Tadeo et al. (2005) highlight the usefulness of these functions for environmental analyses.

along a particular direction vector defined by the researcher, which might represent the preferences of policymakers, firm managers or society regarding the trade-off between economic and ecological performance.

After defining the concepts of eco-performance and directional distance function, following the approach by Kortelainen (2008), we suggest an index for measuring dynamic eco-performance and its determinants based on the computation of *Luenberger* indices (Chambers et al. 1996). In order to assess the change in eco-performance of a given DMU between adjacent periods 0 and 1, let us first set the technology of period 0 as the benchmark and assess eco-performance change by the difference in the directional distance functions of observations 0 and 1 to that technology. Formally:

$$\begin{aligned}\text{Eco}-\text{performance change}^0 = \text{EPCh}^0 = \Big[&\vec{D}^0\left(v^0,\mathbf{p}^0;\mathbf{g}=\left(g_v,-\mathbf{g_p}\right)\right)\\ &-\vec{D}^0\left(v^1,\mathbf{p}^1;\mathbf{g}=\left(g_v,-\mathbf{g_p}\right)\right)\Big]\end{aligned} \tag{5}$$

Alternatively, eco-performance change can be measured regarding the technology of period 1:

$$\begin{aligned}\text{Eco}-\text{performance change}^1 = \text{EPCh}^1 = \Big[&\vec{D}^1\left(v^0,\mathbf{p}^0;\mathbf{g}=\left(g_v,-\mathbf{g_p}\right)\right)\\ &-\vec{D}^1\left(v^1,\mathbf{p}^1;\mathbf{g}=\left(g_v,-\mathbf{g_p}\right)\right)\Big]\end{aligned} \tag{6}$$

Following Chambers et al. (1996), the *Luenberger eco-performance indicator* assessing the change in eco-performance over periods 0 and 1 is computed as the arithmetic mean of the two indices of eco-performance change in expressions (5) and (6):[4]

$$\begin{aligned}\text{LEPCh}^{0,1}\left[v^0,\mathbf{p}^0,v^1,\mathbf{p}^1;\mathbf{g}=\left(g_v,-\mathbf{g_p}\right)\right] = \frac{1}{2}\Big[&\Big\langle\vec{D}^0\left(v^0,\mathbf{p}^0;\mathbf{g}=\left(g_v,-\mathbf{g_p}\right)\right)-\vec{D}^0\left(v^1,\mathbf{p}^1;\mathbf{g}=\left(g_v,-\mathbf{g_p}\right)\right)\Big\rangle\\ &+\Big\langle\vec{D}^1\left(v^0,\mathbf{p}^0;\mathbf{g}=\left(g_v,-\mathbf{g_p}\right)\right)-\vec{D}^1\left(v^1,\mathbf{p}^1;\mathbf{g}=\left(g_v,-\mathbf{g_p}\right)\right)\Big\rangle\Big]\end{aligned} \tag{7}$$

In the spirit of the *Malmquist* productivity index decomposition (Färe et al. 1994) used by Kortelainen (2008)[5], here we decompose the *Luenberger* indicator of eco-performance change into

---

[4] A positive record for this indicator would point to an improvement in eco-performance, whereas negative scores mean that eco-performance has worsened.

two mutually exclusive elements representing, respectively, *eco-efficiency change* and *technical change*.

As already commented, flexibility is one of the primary advantages of directional distance functions, enabling researchers to evaluate performance in different directions representing either their own preferences or those of policymakers. Thus, before proceeding with the de-composition of eco-performance change, let us assume a scenario in which our interest lies in evaluating the extent by which all environmental pressures can be proportionally or radially reduced without decreasing value added. The directional distance function that assesses this proportion in period t provides a measure of eco-efficiency and is computed as:

$$\mathrm{Eco-efficiency}^{t} = \mathrm{EEff}^{t} = \vec{\mathrm{D}}^{t}\left[\mathrm{v}^{t},\mathbf{p}^{t};\,\mathbf{g}=\left(0,-\mathbf{p}^{t}\right)\right]=\mathrm{Sup}\left[\beta\,\middle|\left((1-\beta)\mathbf{p}^{t}\right)\in \mathrm{PRS}^{t}\left(\mathrm{v}^{t}\right)\right] \quad (8)$$

$\mathbf{g}=\left(0,-\mathbf{p}^{t}\right)$ being the direction vector that represents the abovementioned preferences.

Furthermore, the change in eco-efficiency between periods 0 and 1 in this scenario can be evaluated as the difference in the directional distance functions of observations 0 and 1 with respect to their respective contemporaneous technologies:

$$\mathrm{EEffCh}^{0,1}\left[\mathrm{v}^{0},\mathbf{p}^{0},\mathrm{v}^{1},\mathbf{p}^{1};\mathbf{g}=(0,-\mathbf{p})\right]=\left[\vec{\mathrm{D}}^{0}\left(\mathrm{v}^{0},\mathbf{p}^{0};\,\mathbf{g}=\left(0,-\mathbf{p}^{0}\right)\right)-\vec{\mathrm{D}}^{1}\left(\mathrm{v}^{1},\mathbf{p}^{1};\,\mathbf{g}=\left(0,-\mathbf{p}^{1}\right)\right)\right] \quad (9)$$

Accordingly, this indicator measures the increase/decrease in environmental pressures due to the difference of eco-efficiency between periods 0 and 1.

On the other hand, technical change in this scenario can be assessed by comparing value add-ed and environmental pressures in period 0 with respect to the technology of periods 0 and 1, respectively. Formally:

$$\mathrm{TechCh}^{0,1}\left[\mathrm{v}^{0},\mathbf{p}^{0},\mathrm{v}^{1},\mathbf{p}^{1};\mathbf{g}=\left(0,-\mathbf{p}^{0}\right)\right]=\left[\vec{\mathrm{D}}^{1}\left(\mathrm{v}^{0},\mathbf{p}^{0};\,\mathbf{g}=\left(0,-\mathbf{p}^{0}\right)\right)-\vec{\mathrm{D}}^{0}\left(\mathrm{v}^{0},\mathbf{p}^{0};\,\mathbf{g}=\left(0,-\mathbf{p}^{0}\right)\right)\right] \quad (10)$$

or, alternatively, using the observation in period 1 as a basis of comparison:

[5] Boussemart et al. (2003) compare the relative performance of *Malmquist* and *Luenberger* indices.

$$\text{TechCh}^{0,1}\left[\text{v}^0,\mathbf{p}^0,\text{v}^1,\mathbf{p}^1;\mathbf{g}=\left(0,-\mathbf{p}^1\right)\right]=\left[\vec{\text{D}}^1\left(\text{v}^1,\mathbf{p}^1;\mathbf{g}=\left(0,-\mathbf{p}^1\right)\right)-\vec{\text{D}}^0\left(\text{v}^1,\mathbf{p}^1;\mathbf{g}=\left(0,-\mathbf{p}^1\right)\right)\right] \quad (11)$$

Taking the average of expressions (10) and (11) yields:

$$\begin{aligned}\text{TechCh}^{0,1}\left[\text{v}^0,\mathbf{p}^0,\text{v}^1,\mathbf{p}^1;\mathbf{g}=\left(0,-\mathbf{p}\right)\right]=\frac{1}{2}\Big[&\left\langle\vec{\text{D}}^1\left(\text{v}^0,\mathbf{p}^0;\mathbf{g}=\left(0,-\mathbf{p}^0\right)\right)-\vec{\text{D}}^0\left(\text{v}^0,\mathbf{p}^0;\mathbf{g}=\left(0,-\mathbf{p}^0\right)\right)\right\rangle\\&+\left\langle\vec{\text{D}}^1\left(\text{v}^1,\mathbf{p}^1;\mathbf{g}=\left(0,-\mathbf{p}^1\right)\right)-\vec{\text{D}}^0\left(\text{v}^1,\mathbf{p}^1;\mathbf{g}=\left(0,-\mathbf{p}^1\right)\right)\right\rangle\Big]\end{aligned} \quad (12)$$

This indicator of technical change measures the increase/decrease in environmental pressures due to the shift in technology between periods 0 and 1.

Joining together efficiency change and technological change in expressions (9) and (12), respectively, yields what we call here the *proportional Luenberger eco-performance change indicator*, which is formally expressed as:

$$\begin{aligned}\text{LEPCh}^{0,1}\left[\text{v}^0,\mathbf{p}^0,\text{v}^1,\mathbf{p}^1;\mathbf{g}=\left(0,-\mathbf{p}\right)\right]=&\ \text{EEffCh}^{0,1}\left[\text{v}^0,\mathbf{p}^0,\text{v}^1,\mathbf{p}^1;\mathbf{g}=\left(0,-\mathbf{p}\right)\right]\\&+\text{TechCh}^{0,1}\left[\text{v}^0,\mathbf{p}^0,\text{v}^1,\mathbf{p}^1;\mathbf{g}=\left(0,-\mathbf{p}\right)\right]\end{aligned} \quad (13)$$

This indicator measures the change in eco-performance and its determinants, eco-efficiency change and technical change, assessed in a direction that reduces all environmental pressures proportionally while maintaining value added. This decomposition would be equivalent to the dynamic decomposition of eco-performance proposed by Kortelainen (2008), but computed using *Luenberger* indices and directional distance functions instead of *Malmquist* indices and conventional *Shephard*'s distances. Nonetheless, the assumption of proportionality might be overly restrictive as it does not allow modelling some preferences regarding the trade-off between economic performance and ecological performance, which might be of interest to researchers and/or policymakers.[6]

On the contrary, the use of directional distance functions and *Luenberger* indices makes it possible to assess eco-performance change in terms other than radial or proportional measures.

[6] Furthermore, slacks in value added and environmental pressures would not be accounted for under this assumption, when they might be an important source of inefficiency (Mahlberg and Sahoo, 2011).

Let us therefore consider a scenario in which policymakers are interested in assessing the change in eco-performance in a scenario in which only an environmental pressure or group of pressures, denoted by i, are reduced without decreasing economic value added and with no increase in the remaining pressures, which are denoted by –i. In this scenario, the directional distance function that assesses eco-efficiency in period t is:

$$\text{Eco}-\text{efficiency}_{i}^{t}=\text{EEff}_{i}^{t}=\vec{D}_{i}^{t}\left[v^{t},\mathbf{p}^{t};\mathbf{g}=\left(0,(-\mathbf{p}_{i}^{t},\mathbf{0})\right)\right]=\text{Sup}\left[\beta_{i}\,\middle|\left((1-\beta_{i})\mathbf{p}_{i}^{t},\mathbf{p}_{-i}^{t}\right)\in \text{PRS}^{t}\left(v^{t}\right)\right] \quad (14)$$

Furthermore, eco-efficiency change between periods 0 and 1 in this scenario is:

$$\begin{aligned}\text{EEffCh}_{i}^{0,1}\left[v^{0},\mathbf{p}^{0},v^{1},\mathbf{p}^{1};\mathbf{g}=\left(0,(-\mathbf{p}_{i},\mathbf{0})\right)\right]=&\left[\vec{D}_{i}^{0}\left(v^{0},p^{0};\mathbf{g}=\left(0,\left(-\mathbf{p}_{i}^{0},\mathbf{0}\right)\right)\right)\right.\\&\left.-\vec{D}_{i}^{1}\left(v^{1},p^{1};\mathbf{g}=\left(0,\left(-\mathbf{p}_{i}^{1},\mathbf{0}\right)\right)\right)\right]\end{aligned} \quad (15)$$

while technical change between 0 and 1 is:

$$\begin{aligned}\text{TechCh}_{i}^{0,1}\left[v^{0},\mathbf{p}^{0},v^{1},\mathbf{p}^{1};\mathbf{g}=\left(0,(-\mathbf{p}_{i},\mathbf{0})\right)\right]=\frac{1}{2}&\left[\left\langle\begin{array}{l}\vec{D}_{i}^{1}\left(v^{0},\mathbf{p}^{0};\mathbf{g}=\left(0,\left(-\mathbf{p}_{i}^{0},\mathbf{0}\right)\right)\right)\\-\vec{D}_{i}^{0}\left(v^{0},\mathbf{p}^{0};\mathbf{g}=\left(0,\left(-\mathbf{p}_{i}^{0},\mathbf{0}\right)\right)\right)\end{array}\right\rangle\right.\\&\left.+\left\langle\begin{array}{l}\vec{D}_{i}^{1}\left(v^{1},\mathbf{p}^{1};\mathbf{g}=\left(0,\left(-\mathbf{p}_{i}^{1},\mathbf{0}\right)\right)\right)\\-\vec{D}_{i}^{0}\left(v^{1},\mathbf{p}^{1};\mathbf{g}=\left(0,\left(-\mathbf{p}_{i}^{1},\mathbf{0}\right)\right)\right)\end{array}\right\rangle\right]\end{aligned} \quad (16)$$

Finally, with this direction the indicator of eco-performance change between periods 0 and 1, which we will refer to as the *pressure-specific Luenberger eco-performance change indicator* can be defined for pressure or group of pressures i as:

$$\begin{aligned}\text{LEPCh}_{i}^{0,1}\left[v^{0},\mathbf{p}^{0},v^{1},\mathbf{p}^{1};\mathbf{g}=\left(0,(-\mathbf{p}_{i},\mathbf{0})\right)\right]=&\ \text{EEffCh}_{i}^{0,1}\left[v^{0},\mathbf{p}^{0},v^{1},\mathbf{p}^{1};\mathbf{g}=\left(0,(-\mathbf{p}_{i},\mathbf{0})\right)\right]\\&+\text{TechCh}_{i}^{0,1}\left[v^{0},\mathbf{p}^{0},v^{1},\mathbf{p}^{1};\mathbf{g}=\left(0,(-\mathbf{p}_{i},\mathbf{0})\right)\right]\end{aligned} \quad (17)$$

The main interest in assessing dynamic eco-performance and its determinants using directional distance functions and pressure-specific directions is that both proportional and non-proportional *Luenberger* indicators could yield different rates of eco-performance growth, eco-efficiency change and technical change.[7] What is more, growth estimates are also expected to be different depending on the direction chosen for the reduction of environmental pressures. In our opinion, these features could yield worthwhile information to policymakers, helping them to design better environmental policies. Figure 1 illustrates this assertion regarding technical change.

In the picture we consider a technology which generates an added value v and two environmental pressures, p_1 and p_2, and is represented by the PRS(v). For the sake of simplicity, we evaluate technical change projecting the observation of DMU k in period 1, namely k^1, onto the eco-efficient frontiers of periods 0 and 1. Projecting in a direction that only reduces p_2 while maintaining value added and p_1 at their observed levels allows us to assess the potential saving achievable through technical change. This potential is measured by the segment FE and comes from the difference between the directional distance functions of observation k^1 projected onto the eco-efficient frontiers of periods 1 and 0, respectively. However, with a direction that only reduces pressure p_1, always maintaining value added and p_2, the potential saving due to the technical change occurred between periods 0 and 1 is measured by CD. Figure 1 also shows the potential saving in pressures p_1 and p_2 due to technical change in a scenario where directional distance functions are computed assuming proportional reductions in both pressures. Noticeably, the contribution of technical change to the change in eco-performance will be quite different depending on the scenario, i.e., the direction vector, considered to assess the change in eco-performance.

2.2. Computing directional distance functions with Data Envelopment Analysis

Data Envelopment Analysis is a well-known non-parametric approach to efficiency measurement initially proposed by Charnes et al. (1978) that has been used in hundreds of empirical

[7] Furthermore, our DEA-based approach could also model other scenarios involving, for example, improvements in economic performance while environmental pressures are maintained or simultaneous increases in value added and decreases in environmental pressures.

papers (see Cook and Seiford 2009). In essence, this technique uses mathematical programming to compare the position of a DMU to best observed practices in the sample it belongs to, in terms of a performance indicator (see Cooper et al. 2007 for details). Given the absence of prices for environmental pressures in our case study, an important advantage of DEA over other approaches to building composite indicators[8] is that the scheme of weightings used to aggregate environmental pressures is endogenously generated at DMU level. Based on the so-called *benefit of the doubt* principle (Cherchey et al. 2007), DEA assigns to each DMU evaluated the set of weightings that rates it in the most favourable light when compared to all other DMUs in the sample using the same set of weightings.[9]

Using a direction that reduces all environmental pressures proportionally, the DEA-based program required to compute the directional distance function of an observation or DMU k′ on period 0 with respect to its contemporaneous technology is:

$$\begin{aligned} &\text{Maximize}_{\beta_{k'},z_k}\ \vec{D}^0\left[v^0,\mathbf{p}^0;\mathbf{g}=\left(0,-\mathbf{p}^0\right)\right]=\beta_{k'} \\ &\text{subject to:} \\ &\qquad v^0_{k'} \le \textstyle\sum_{k=1}^{K} z_k v^0_k \qquad\qquad\qquad\qquad\quad \text{(i)} \\ &\qquad \left(1-\beta_{k'}\right)p^0_{k'n} \ge \textstyle\sum_{k=1}^{K} z_k p^0_{kn} \qquad n=1,\dots,N \quad \text{(ii)} \\ &\qquad z_k \ge 0 \qquad\qquad\qquad\qquad\qquad\quad k=1,\dots,K \quad \text{(iii)} \end{aligned} \tag{18}$$

with z_k standing for the weighting of each DMU k in the composition of the *virtual* eco-efficient observation on the technological frontier DMU k′ is compared to.

Furthermore, computing the directional distance function of DMU k′ in this scenario in period 0 with respect to the technology in period 1 requires solving the following linear program:

---

[8] Zhou et al. (2006) compares several aggregating methods to construct composite environmental indicators.

[9] In some cases the optimal set of weightings can assign great importance (weightings) to pressures which are scarcely relevant for managers or policymakers. Kuosmanen and Kortelainen (2005) proposed dealing with this problem by imposing additional *a priori* restrictions on the relative importance of different environmental pressures; Allen and Thanassoulis, 2004 reviews several techniques to incorporate weighting restrictions in DEA models.

$$\text{Maximize}_{\beta_{k'},z_k}\ \vec{D}^1\left[v^0,\mathbf{p}^0,v^1,\mathbf{p}^1;\mathbf{g}=\left(0,-\mathbf{p}^0\right)\right]=\beta_{k'}$$
subject to:
$$\begin{array}{lll} v^0_{k'}\leq\sum_{k=1}^{K}z_k v^1_k & & \text{(i)} \\ \left(1-\beta_{k'}\right)p^0_{k'n}\geq\sum_{k=1}^{K}z_k p^1_{kn} & n=1,\ldots,N & \text{(ii)} \\ z_k\geq 0 & k=1,\ldots,K & \text{(iii)} \end{array} \qquad (19)$$

On the other hand, with a direction vector that reduces one pressure alone or a group of environmental pressures, the contemporaneous directional distance function of DMU k′ in period 0 and the directional distance function in period 0 with respect to the technology in period 1 can be computed, respectively, as:

$$\text{Maximize}_{\beta_{ik'},z_k}\ \vec{D}^0\left[v^0,\mathbf{p}^0;\mathbf{g}=\left(0,\left(-\mathbf{p}^0_i,\mathbf{0}\right)\right)\right]=\beta_{ik'}$$
subject to:
$$\begin{array}{lll} v^0_{k'}\leq\sum_{k=1}^{K}z_k v^0_k & & \text{(i)} \\ \left(1-\beta_{ik'}\right)p^0_{ik'}\geq\sum_{k=1}^{K}z_k p^0_{ik} & i\in n \text{ and } i\notin -i & \text{(ii)} \\ p^0_{-ik'}\geq\sum_{k=1}^{K}z_k p^0_{-ik} & n=1,\ldots,N & \text{(iii)} \\ z_k\geq 0 & k=1,\ldots,K & \text{(iv)} \end{array} \qquad (20)$$

and

$$\text{Maximize}_{\beta_{ik'},z_k}\ \vec{D}^1\left[v^0,\mathbf{p}^0,v^1,\mathbf{p}^1;\mathbf{g}=\left(0,\left(-\mathbf{p}^0_i,\mathbf{0}\right)\right)\right]=\beta_{ik'}$$
subject to:
$$\begin{array}{lll} v^0_{k'}\leq\sum_{k=1}^{K}z_k v^1_k & & \text{(i)} \\ \left(1-\beta_{ik'}\right)p^0_{ik'}\geq\sum_{k=1}^{K}z_k p^1_{ik} & i\in n \text{ and } i\notin -i & \text{(ii)} \\ p^0_{-ik'}\geq\sum_{k=1}^{K}z_k p^1_{-ik} & n=1,\ldots,N & \text{(iii)} \\ z_k\geq 0 & k=1,\ldots,K & \text{(iv)} \end{array} \qquad (21)$$

In programs (18) to (21) we have assumed that the technology exhibits constant returns to scale by allowing the sum of the elements of the intensities vector to be free (Banker et al. 1984); Picazo-Tadeo et al. (2012) provide a detailed justification of this assumption in the framework of eco-efficiency measurement. Furthermore, minor changes of notation are needed to formulate the programs required to obtain the contemporaneous directional distance functions of observation k′ in period 1, as well as the directional distance functions with respect to the technology in period 0, which is left to readers.

3. Dynamic eco-efficiency in greenhouse gas emissions in the European Union-27

3.1. Dataset and variables

In this paper, we use data on EU-27 member state emissions of the three main GHGs for which reduction targets were agreed in the *Kyoto Protocol*, namely, carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4). Jointly these gases represent around 98% of aggregate GHG emissions in the EU-27. Figures come from the *Annual European Union Greenhouse Inventory 1990-2010* of the *European Environmental Agency* (EEA, 2012a)[10] and cover the period 1990-2010. Concerning GHG-emitting sectors, our aggregates include emissions from the sectors of energy, industrial processes, solvents and other product use, agriculture, waste and, finally, others. Furthermore, emissions are measured in CO_2 equivalent million tons. Table 1 displays the amount of emissions in 1990 and 2010.

The economic performance of EU-27 countries is accounted for by the value of goods and services produced, which is measured by real Gross Domestic Product (GDP) (constant US$, base 2000). The data come from the *World Bank*.[11] Furthermore, we have calculated the intensity of emissions as the ratio of GHG emissions to GDP, which in the EU-27 has dropped from an average of 0.79 CO_2 equivalent tons per 1,000 US$ of GDP in 1990-92 to 0.49 in 2008-10. Reductions are particularly significant in the Eastern countries that joined the EU in 2004 and 2007, which is highly relevant considering that the intensity of GHG emissions in these economies was noticeably higher. Meanwhile, reductions in countries from the former European Union-15 (EU-15) are also significant, albeit to a lesser extent.[12] The patterns of behaviour for the intensity of emissions of individual GHG are rather similar.

---

[10] Accessed on 9th October 2012 through http://dataservice.eea.europa.eu

[11] Accessed on 9th October 2012 through http://databank.worldbank.org

[12] Figures on emission intensities for individual EU-27 members are available upon request.

3.2. Dynamic eco-performance: technical change versus eco-efficiency change

Dynamic eco-performance has been assessed for each member of the EU-27 in four scenarios which contemplate different objectives regarding GHG reduction, namely, proportional reduction of all three gases considered and specific reductions of CO_2, N_2O and CH_4, respectively. Results are in Table 2, which displays countries' average growth rates in the *Luenberger eco-performance change indicator* and its determinants, *eco-efficiency change* and *technical change*, over the period 1990-2010. Given the additive nature of directional distance functions, it is worth to remembering here that the growth rate of eco-performance can be obtained as the sum of the growth rates of eco-efficiency and technical change.

Before commenting on these results, let us say that in some cross-period programs, i.e., programs in which the observation of one period is compared to the technology of a different period, the observation under evaluation remained outside of the pressure-generating technology set, so no feasible solution existed for these *super-efficient* observations.[13] Infeasibility has occurred for some cross-period programs involving three countries usually located on the eco-efficient frontier, namely, Sweden, Malta and Luxembourg, in addition to the United Kingdom in some years at the end of the period studied. In these cases, temporal averages for eco-performance and technical change in the period 1990-2010 have been computed only if three quarters or more of the twenty year-to-year growth rates were available. Moreover, in order to maintain the decomposition of eco-performance additive, averages for eco-performance change and its determinants for the EU-27 have been computed excluding the four abovementioned countries.

Moving on to the results, in the scenario where all GHG are reduced by the same proportion, i.e., *proportional GHG eco-performance*, eco-performance in the EU-27 has improved during the period 1990-2010 by an annual average rate of 1.36%. Moreover, with an average annual

[13] Briec and Kerstens (2009) discuss about infeasibility and directional distance functions in the framework of the *Luenberger* productivity indicator, and explore whether there exist any solutions that remedy the problem in an economically meaningful way; they conclude that no easy solution exists.

growth of 1.23%, technical progress has been by far the main driving force behind the increase in eco-performance, while eco-efficiency has scarcely grown at an average rate of 0.12%.

The countries that display the highest growth rates in eco-performance are The Netherlands, Germany, Austria and some Scandinavian countries such as Finland and Denmark. At the opposite end of the scale, the poorest performance growth is observed in the Eastern countries incorporated into the EU-27 in years 2004 and 2007, particularly Hungary, Romania and Bulgaria, and also in some Southern European countries such as Spain and Portugal. Concerning countries driving technical change, four economies are found to be innovators; while the United Kingdom is an innovator only in a few years at the end of the period studied, Luxemburg, Malta and Sweden are identified as innovators in almost all consecutive year-to-year periods. Finally, the greatest improvements in eco-efficiency correspond to Germany, The Netherlands and the United Kingdom[14], whereas eco-efficiency has even deteriorated in some countries such as Italy, Spain or Portugal. In general terms, these results coincide with those obtained by Kortelainen (2008).

In the scenarios where eco-performance is assessed at specific GHG level, i.e., *pressure-specific eco-performance*, the overall result that technical change has been the main driving force behind eco-performance growth in the EU-27 holds. Notwithstanding, some differences between air pollutants are worth mentioning and add interest to the approach proposed in this paper. Eco-performance in CO_2, N_2O and CH_4 emissions enhanced between 1990 and 2010 at average annual rates of 0.73%, 1.39% and 1.02%, respectively. However, eco-efficiency has remained virtually stagnant in all three cases and deteriorated at average annual rates of 0.12% and 0.15% for CO_2 and CH_4, respectively. Lastly, the greatest technical change at air pollutant level has been achieved in the cases of N_2O and CH_4 emissions, with growth rates of 1.23% and 1.16%.

---

[14] Recent studies have also found important improvements in ecological-economic performance/efficiency in the United Kingdom (Kortelainen, 2008; Marrero, 2010).

In order to provide further insight into the relative levels of eco-efficiency among EU-27 member states, Table 3 displays the averages of eco-efficiency at both the beginning and also the end of the period analysed. For the period 2008-10, GHG proportional eco-efficiency records an average across EU-27 member states of 0.465, indicating that a proportional reduction of all three emissions of 46.5% could be achieved while maintaining value added at observed levels. Furthermore, averages of eco-efficiency scores for CO_2, N_2O and CH_4 are 0.582, 0.575 and 0.603, respectively. Hence, although differences among pollutants are relatively small, N_2O records the best eco-efficiency average and CH_4 the worst. Concerning individual countries, the eco-efficient peers that under-performers are compared to are Luxembourg, Malta, Sweden and the United Kingdom, while other highly eco-efficient economies are Austria, The Netherlands and Germany; conversely, by far the worst eco-efficiency is observed in Eastern European economies that joined the EU-27 in 2004 and 2007, such as Bulgaria, Romania, Estonia and Poland. The eco-efficiency profile observed in 1990-92 is quite similar, with some core European countries and some Scandinavian economies among the most eco-efficient and the most recent EU members occupying the bottom of the ranking.

4. Discussion and policy implications

Global warming and climate change are, as noted in the Introduction, a matter of increasing concern for policymakers all around the world. Before the 1990s, standards only existed for a few air pollutants in the European Union (EU). However, the 5th *Environmental Action Program* established a more integrating series of long-term objectives for air quality by setting ceilings for pollutants such as CO_2. Under the *Kyoto Protocol*, the members of the former EU-15 agreed to cut down their collective GHG emissions by 2012 to 8% below the levels recorded in the base year 1990. Later on, in 2002, the 6th *Environmental Action Program* set out the framework for environmental policymaking in the European Union for the period 2002-2012, also identifying climate change as one area of priority action. In March 2008 the European Council approved the *EU Climate and Energy Package* against climate change, which implemented the so-called *20-20-20 target*, according to which by 2020 the EU should reach a share of 20% of renewables in energy consumption, achieve an energy improvement of 20% and reduce GHG emissions by 20% compared to 1990. What is more, the EU is offering to raise this reduction to 30% if other developed economies agree to do their fair share in a global effort.

According to the *European Environment Agency* (EEA, 2012a), the objective agreed by the EU-15 under the *Kyoto Protocol* is on course to be overachieved and emissions in 2010 are estimated to have been reduced by 10.6% as compared to 1990. Although almost all EU-15 members are on track to reach their individual *Kyoto* targets, differences among countries are significant with some Mediterranean economies having raised their emissions above the quotas of responsibility on the global target they were assigned. In addition, most of the Eastern European countries that joined the EU in 2004 and 2007 have also agreed significant reduction targets so the combined reduction of GHG emissions in 2010 for the EU-27 has already reached 15.4% (see Table 1). In addition, according to the EEA (2012b), most EU members forecast that in 2020 their emissions outside the *EU Emissions Trading System*[15] will be lower than their national targets set under the *EU Climate and Energy Package*. However, European policymakers recognise that further efforts will still be necessary to achieve longer term emission reductions.

Beyond the reduction in GHG emissions achieved in the EU-27 since the 1990s, which has resulted in a considerable enhancement of ecological performance, our results show that when economic performance and ecological performance are jointly considered, there has also been a clear improvement. Furthermore, technological change has been, by far, the main driving force behind eco-performance improvement, while average eco-efficiency has even decreased in regard to some particular air pollutants. Accordingly, one policy conclusion from these results is that more effort is required on behalf of European environmental policymakers to encourage catching-up in eco-efficiency among European members. Research and develop-

[15] Launched in 2005, the *Emissions Trading System* is one of the cornerstones of EU policy against climate change, which works on a *cap and trade* principle; i.e., there is a limit on the emission of certain greenhouse gases, but companies receive emission allowances which they can sell to or buy from one another as needed.

ment policies focused on investigating new emission saving technologies might not be enough if best practices are not later applied in full to production processes and generally to the management of air pollutants by European countries, allowing them to approach the technological frontier.[16]

Differences in eco-efficiency among European countries might be due to different capabilities to jointly manage production processes and the environment, but also to other circumstances such as different levels of development, differences in citizens' environmental awareness or, largely, different production structures.[17] Among most eco-efficient countries in our case study, Luxembourg is the richest economy in the EU-27 and has a productive structure highly oriented towards services, particularly banking and finance. Sweden is also a highly developed European country where, as in other Scandinavian economies, citizens have traditionally shown a high level of environmental awareness. In contrast, less eco-efficient countries, mostly the newer Eastern members of the EU-27, have production structures more dominated by more contaminating industrial activities and, moreover, environmental regulations and environmental awareness on behalf of citizens is more recent than in other Western European countries.

Most of the aforementioned factors affecting countries' eco-efficiency, including citizens' concern for the environment or production structures, only change in the longer term. However, this does not necessarily mean that environmental policy measures aimed at boosting eco-efficiency in the medium and short term cannot be effective. Among others, these policies should focus on aspects such as reducing the intensity of energy consumption in production processes, or *energy intensity*, and decreasing the *intensity of emissions* per unit of energy, which

[16] Strengthening both eco-innovations and eco-efficiency was, in fact, already identified by the EU as a key option to achieve the competitiveness targets in the *Lisbon Agenda* (EC, 2010).

[17] Production structures are, in turn, influenced by countries' endowment of productive resources and, also, by international trade and flows of foreign direct investment; i.e., some developed countries might reallocate polluting activities in developing countries with lower environmental standards (*pollution haven hypothesis*).

mostly depends on energy sources; i.e., while fossil fuels such as coal or oil generate greater GHG emissions, renewable energies result in lower emissions.

Consequently, on the one hand, more incentives are needed in the EU-27 to reduce emissions by switching to cleaner sources of energy; policy measures in this direction should play an important role in the case of pollutants such as methane and, also, in the newer Eastern members of the EU-27, where the poorest scores of eco-efficiency are recorded, according to our results in this paper. On the other hand, environmental policies aimed at increasing the use of technologies that reduce the energy dependence of production processes, thus permitting energy improvements, are also highly advisable to enhance eco-efficiency. Insofar as economic–ecologic inefficiencies are more than likely related to poor technical management of production factors, i.e., overuse of inputs, including energy, more general policy measures based on promoting skills and managerial capabilities would also be a welcome means of reducing emissions.

Clearly, most of the abovementioned policy recommendations are not new, as some of them constitute keystones of current environmental policymaking against climate change in the EU. Notwithstanding, in our view, performing studies aimed at providing scientific grounds to European environmental policies, particularly from renewed perspectives as we do in this paper by combining economic and environmental performance, is a must for researchers. In this line of research, a recent paper by Mahlberg et al. (2011) uses *Malmquist* indices to analyse the driving forces of eco-productivity change in 14 European Union member countries for the period 1995–2004; furthermore, aggregate national emissions of GHG are considered an undesirable output of production processes. Contrary to our approach here, professor Mahlberg and colleagues account for labour and capital in their analysis and isolate the contribution of both inputs and GHG emissions to the change in productivity and its determinants. The foremost result is that eco-productivity growth in the period was mostly driven by improved environmental conditions.

Moreover, Marrero (2010) has recently estimated that the elasticity between aggregate energy consumption and GHG emissions in the EU is significantly greater than zero, but below unity. Accordingly, insofar all three targets in the *EU Climate and Energy Package* are strongly related to each other, further reductions in energy consumption will be required to achieve the objective for GHG emissions. Professor Marrero also points out that an additional boost to efficiency would be required to achieve the goal for emissions. Without intending to go into great detail, other papers that also provide interesting insights for European policies against climate change are Bengochea (2012), Camarero et al (2013a,b) and Duro and Padilla (2013).

5. Concluding remarks and suggestions for further research

The concept of *ecological-economic performance*, popularly known as *eco-performance*, was developed in the 1990s as an empirical tool to approach the more elusive notion of *sustainability*. After two decades of research, researchers continue to assess the relationship between economic activity and the environment, riding a wave of literature in the field of ecological economics. Building on previous work by Kortelainen (2008) and Picazo-Tadeo et al. (2012), this paper contributes an approach to assess dynamic eco-performance and its determinants, namely, change in ecological-economic efficiency and technical change, at the level of specific environmental pressures exerted by economic activity. In doing so, *Data Envelopment Analysis* techniques, directional distance functions and *Luenberger* indices are used. In our view, the strongest point of this approach is that it allows us to assess eco-performance in different scenarios that might represent the preferences of policymakers or society as regards the trade-off between economic performance and ecological performance. Our approach is used to assess dynamic eco-performance in the emissions of greenhouse gases in the European Union-27 over the period 1990-2010. The main interest of this analysis is, in our opinion, that it provides European policymakers with a joint assessment of both ecological and economic issues related to greenhouse gases, which might help them design better policies to combat climate change.

Our main findings are summarised as follows. First, eco-performance in the European Union-27 has noticeably improved between 1990 and 2010 in all three GHG considered, namely, carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4), the greatest improvement corresponding to N_2O and CH_4. Second, changes in eco-performance are almost entirely due to technical progress, while average eco-efficiency has remained practically stagnant and even deteriorated in the case of CO_2 and CH_4. Third, some core European economies, such as The Netherlands, Germany and Austria, as well as Scandinavian countries, display the highest growth rates in eco-performance, while the lowest rates are observed in Eastern European countries, particularly Hungary, Romania and Bulgaria, and some Southern European countries such as Spain and Portugal. Fourth and finally, Luxembourg, Malta, Sweden and the United Kingdom are innovative countries, while the Eastern countries that joined the European Union in 2004 and 2007 perform the furthest away from their technological frontiers.

The main policy implication from these results is that, in addition to strengthening research and development policies on eco-innovations, further environmental policy measures are needed in order to boost catching-up in eco-efficiency among European Union members; in other words, measures aimed at facilitating the use of available technologies that reduce the emission of greenhouse gases are required. These environmental policies should help to improve both energy and emission intensities, particularly in the cases of greenhouse gases N_2O and CH_4 and, also, in most of the Eastern countries recently incorporated into the European Union-27, which record, by far, the lowest levels of eco-efficiency.

As a final point, we would like to mention certain clarifications and limitations that should be taken into account when interpreting the results of our empirical application, together with some lines for future work. On the one hand, our results concerning potential greenhouse gas reductions are not measures of countries' absolute ecological performance, but rather measures of ecological performance relative to economic performance. Moreover, potential reductions in air pollutants must also be understood in relative terms, as absolute reductions would be different in two countries awarded the same score of eco-efficiency if they initially have different levels of emissions. Both these circumstances should be accounted for when designing environmental policies aimed at boosting sustainability. In this sense, eco-efficiency improvement does not necessarily boost countries' sustainability, as the latter demands taking into account the absolute value of emissions and the capacity of the environment to absorb them. However, improving eco-efficiency is often the least costly way of reducing the environmental pressures that jeopardise sustainability; also, policies aimed at improving eco-efficiency are easier to implement than more drastic measures restricting the level of economic activity. Accordingly, improving eco-efficiency could be considered an essential ingredient to obtain the environmental improvements that society demands at a minimum cost.

On the other hand, future work in this bourgeoning field of research should include methodological challenges such as integrating a schedule of non-linear preferences in the construction of the composite indicator of environmental pressure involved in DEA-based models of eco-efficiency; assessing countries' eco-performance while controlling for their different production structures or foreign investment flows; and, also, computing other non-radial slack-based measures of eco-performance with directional distance functions. Furthermore, from an empirical point of view, one interesting avenue for research that in our opinion would be of great interest to policymakers could be to extend our DEA-based directional distance function approach to the analysis of broader notions of eco-performance including, in addition to economic and ecological performance, other dimensions of *sustainability* such as social performance.

Acknowledgments

This research has been co-funded by the Spanish Ministry of Economy and Competitiveness (projects AGL2010-17560-C02-02, ECO2011-30260-C03-01 and ECO2012-32189) and the Generalitat Valenciana (PROMETEO 2009/098).

References

Allen, R., Thanassoulis, E., 2004. Improving envelopment in data envelopment analysis. European Journal of Operational Research 154(2), 363–379.

Banker, R., Charnes, R., Cooper, W., 1984. Some models for estimating technical and scale inefficiencies in Data Envelopment Analysis. Management Science 30(9), 1078-1092.

Beltrán-Esteve, E., Gómez-Limón, J.A., Picazo-Tadeo, A.J., Reig-Martínez, E., 2013. A metafrontier directional distance function approach to assessing eco-efficiency. Journal of Productivity Analysis, in press; doi 10.1007/s11123-012-0334-7.

Bengochea, A., Faet-Gallur, O., 2012. Renewable energies and CO_2 emissions in the European Union. Energy Sources, Part B: Economics, Planning, and Policy, 7(2), 121-130.

Boussemart, J.P., Briec, W., Kerstens, K., Poutineau, J.C., 2003. Luenberger and Malmquist productivity indices: theoretical comparisons and empirical illustration. Bulletin of Economic Research 55, 391–405.

Briec, W., Kerstens, K., 2009. Infeasibility and directional distance functions with application to the determinateness of the Luenberger productivity indicator. Journal of Optimization Theory and Applications 141, 55–73.

Camarero, M., Castillo, J., Picazo-Tadeo, A.J., Tamarit, C., 2013a. Eco-efficiency and convergence in OECD countries. Environmental and Resource Economics, in press; doi 10.1007/s10640-012-9616-9.

Camarero, M., Picazo-Tadeo, A.J., Tamarit, C., 2013b. Are the determinants of CO_2 emissions converging among OECD countries? Economics Letters 118, 159-162.

Chambers, R., Chung, Y., Färe, R., 1998. Profit, directional distance functions and Nerlovian efficiency. Journal of Optimization Theory and Applications 98(2), 351-364.

Chambers, R.G., Färe, R., Grosskopf, S., 1996. Productivity growth in APEC countries. Pacific Economic Review, 1996, 1(3): 181-90.

Charnes, A., Cooper, W.W., Rhodes, E., 1978. Measuring the efficiency of decision making units. European Journal of Operational Research 2, 429-444.

Cherchye, L., Moesen, W., Rogge, N., van Puyenbroek, T., 2007. An introduction to 'benefit of the doubt' composite indicators. Social Indicators Research 82(1), 111–145.

Cook, W.D., Seiford, L.M., 2009. Data envelopment analysis (DEA)-Thirty years on. European Journal of Operational Research 192, 1-17.

Cooper, W.W., Seiford, L.M., Tone, K., 2007. Data Envelopment Analysis. A comprehensive text with models, applications, references and DEA-Solver software. Springer, New York.

Duro, J.A. and Padilla, E., 2013. Cross-country polarisation in CO_2 emissions per capita in the European Union: Changes and explanatory factors. Environmental and Resource Economics, in press; doi 10.1007/s10640-012-9607-x

Dyckhoff, H., Allen, K., 2001. Measuring ecological efficiency with data envelopment analysis (DEA). European Journal of Operational Research 132, 312–325.

EC, European Commission, 2010. Europe 2020: A European strategy for smart, sustainable and inclusive growth. Communication COM(2010) 2020. Brussels.

EEA, European Environment Agency, 2012b. Greenhouse gas emission trends and projections in Europe 2012. Tracking progress towards Kyoto and 2020 targets. Technical report, 6/2012, Luxembourg.

EEA, European Environmental Agency, 2012a. Annual European Union greenhouse gas inventory 1990–2010 and inventory report 2012. Technical report, 3/2012. Luxembourg.

Färe, R., Grosskopf, S. 2000. Theory and application of directional distance functions. Journal of Productivity Analysis 13, 93-103.

Huppes, G., Ishikawa, M., 2005a. Why eco-efficiency. Journal of Industrial Ecology 9(4), 2-5.

Huppes, G., Ishikawa, M., 2005b. A framework for quantified eco-efficiency analysis. Journal of Industrial Ecology, 9, 25-41.

Huppes, G., Ishikawa, M., 2009. Eco-efficiency guiding micro-level actions towards sustainability: Ten basic steps for analysis. Ecological Economics 68, 1687–1700.

Korhonen, P.J., Luptacik, M., 2004. Eco-efficiency analysis of power plants: an extension of data envelopment analysis. European Journal of Operational Research 154(2), 437-446.

Kortelainen, M., 2008. Dynamic environmental performance analysis: A Malmquist index approach. Ecological Economics 64, 701-715.

Kuosmanen, T., Kortelainen, M., 2005. Measuring eco-efficiency of production with Data Envelopment Analysis. Journal of Industrial Ecology 9, 59-72.

Mahlberg, B., Sahoo, B., 2011. Radial and non-radial decompositions of Luenberger productivity indicator with an illustrative application. International Journal of Production Economics 131, 721–726.

Mahlberg, B., Luptacik, M., Sahoo, B., 2011. Examining the drivers of total factor productivity change with an illustrative example of 14 EU countries. Ecological Economics 72, 60–69.

Malmquist, S., 1953. Index numbers and indifference surfaces. Trabajos de Estadística 4, 209–242.

Marrero, G., 2010. Greenhouse gases emissions, growth and the energy mix in Europe. Energy Economics 32, 1356–1363.

OECD, Organization for Economic Co-operation and Development, 1998. Eco-efficiency, OECD, Paris.

Picazo-Tadeo, A.J., Beltrán-Esteve, M., Gómez-Limón, J.A. 2012. Assessing eco-efficiency with directional distance functions. European Journal of Operational Research 220, 798-809.

Picazo-Tadeo, A.J., Gómez-Limón, J.A., Reig-Martínez, E., 2011. Assessing farming eco-efficiency: A Data Envelopment Analysis approach. Journal of Environmental Management, 92, 1154-1164.

Picazo-Tadeo, A.J., Reig-Martínez, E., Hernández-Sancho, F., 2005. Directional distance functions and environmental regulation. Resource and Energy Economics 27, 131-142.

Schaltegger, S., Synnestvedt, T., 2002. The link between 'green' and economic success: environmental management as the crucial trigger between environmental and economic performance. Journal of Environmental Management 65, 339-346.

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.

WCED, World Commission on Environment and Development, 1987. Our common future. Oxford University Press, Oxford.

Zhang, B., Bi, J., Fan, Z., Yuan, Z., Ge, J., 2008. Eco-efficiency analysis of industrial system in China: a data envelopment analysis approach. Ecological Economics, 68, 306–316.

Zhou, P., Ang, B.W., Poh, K.L., 2006. Comparing aggregating methods for constructing the composite environmental index: an objective measure. Ecological Economics 59, 305–311.

Figure 1

Pressure-generating technology and pressure-specific dynamic eco-efficiency

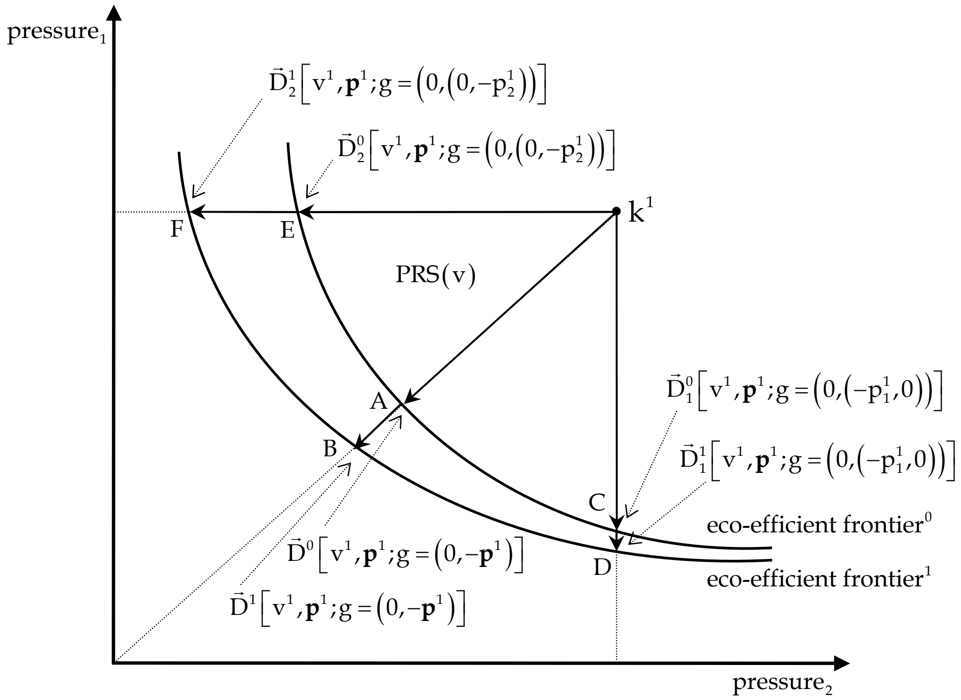

Table 1
Emissions of GHG in the European Union-27 (CO_2 equivalent million tons)

	1990	2010
Carbon dioxide (CO_2)	4,419.9	3,891.3
Nitrous oxide (N_2O)	513.7	334.5
Methane (CH_4)	590.3	400.7
Sulphur hexafluoride (SF_6)	10.9	6.5
Hydrofluorocarbons (HFCs)	27.9	84.5
Perfluorocarbons (PFCs)	20.4	3.4
Aggregated emission (GHG)	5,583.1	4,720.9

Note: Figures on SF_6, HFCs and PFCs emissions are also included to illustrate the lesser importance of these air pollutants in total GHG emission in the EU-27.

Table 2

Dynamic economic-ecological performance in the European Union-27: Eco-efficiency change *versus* technical change

(Averages for the period 1990-2010)

	Proportional GHG eco-performance			Carbon Dioxide (CO_2) eco-performance		
	Luenberger Eco-Performance Change Indicator (LEPCh)	Eco-efficiency Change (EEffCh)	Technical Change (TechCh)	Luenberger Eco-Performance Change Indicator (LEEPCh)	Eco-efficiency Change (EEffCh)	Technical Change (TechCh)
Austria	0.0224	-0.0008	0.0232	0.0238	-0.0067	0.0305
Belgium	0.0241	0.0003	0.0238	0.0080	-0.0021	0.0101
Bulgaria	0.0039	0.0018	0.0020	0.0024	0.0010	0.0014
Cyprus	0.0129	-0.0001	0.0130	-0.0022	-0.0045	0.0023
Czech Republic	0.0078	0.0029	0.0049	0.0039	0.0011	0.0027
Denmark	0.0179	-0.0035	0.0214	0.0118	-0.0031	0.0149
Estonia	0.0059	0.0015	0.0044	0.0036	0.0015	0.0021
Finland	0.0206	0.0012	0.0195	-0.0049	-0.0050	0.0001
France	0.0121	-0.0055	0.0176	0.0121	-0.0055	0.0176
Germany	0.0263	0.0060	0.0203	0.0153	0.0008	0.0146
Greece	0.0128	0.0019	0.0109	0.0038	-0.0031	0.0069
Hungary	0.0058	0.0009	0.0049	0.0051	0.0007	0.0044
Ireland	0.0171	0.0047	0.0125	0.0171	0.0047	0.0125
Italy	0.0165	-0.0047	0.0212	0.0058	-0.0119	0.0176
Latvia	0.0100	0.0037	0.0063	0.0100	0.0037	0.0063
Lithuania	0.0100	0.0048	0.0051	0.0100	0.0048	0.0051
Luxembourg [1]	-	0.0001	-	-	0.0313	-
Malta [1]	-	0.0000	-	-	0.0000	-
Netherlands	0.0315	0.0137	0.0177	0.0135	0.0027	0.0109
Poland	0.0080	0.0036	0.0043	0.0050	0.0021	0.0029
Portugal	0.0111	-0.0038	0.0149	0.0026	-0.0074	0.0100
Romania	0.0043	0.0016	0.0027	0.0044	0.0023	0.0020
Slovak Republic	0.0091	0.0031	0.0060	0.0079	0.0039	0.0040
Slovenia	0.0107	-0.0010	0.0117	0.0051	-0.0019	0.0070
Spain	0.0114	-0.0039	0.0153	0.0046	-0.0059	0.0104
Sweden [1]	-	0.0000	-	-	0.0000	-
United Kingdom [1]	0.0407	0.0176	0.0207	0.0685	0.0224	0.0550
European Union-27 [2]	*0.0136*	*0.0012*	*0.0123*	*0.0073*	*-0.0012*	*0.0085*

Table 2 (continued)

	Nitrous Oxide (N_2O) eco-performance			Methane (CH_4) eco-performance		
	Luenberger Eco-Performance Change Indicator (LEEPCh)	Eco-efficiency Change (EEffCh)	Technical Change (TechCh)	Luenberger Eco-Performance Change Indicator (LEEPCh)	Eco-efficiency Change (EEffCh)	Technical Change (TechCh)
Austria	0.0307	-0.0012	0.0319	0.0299	0.0035	0.0264
Belgium	0.0241	0.0034	0.0208	0.0255	0.0012	0.0243
Bulgaria	0.0022	0.0008	0.0013	0.0017	0.0006	0.0011
Cyprus	0.0099	0.0005	0.0095	-0.0014	-0.0046	0.0032
Czech Republic	0.0050	0.0012	0.0037	0.0058	0.0013	0.0044
Denmark	0.0274	0.0053	0.0222	0.0162	-0.0096	0.0258
Estonia	0.0040	0.0013	0.0028	0.0056	0.0009	0.0047
Finland	0.0186	0.0018	0.0168	0.0209	0.0014	0.0196
France	0.0205	0.0024	0.0181	0.0091	-0.0100	0.0191
Germany	0.0366	0.0102	0.0264	0.0354	0.0119	0.0235
Greece	0.0086	0.0011	0.0075	0.0071	-0.0032	0.0104
Hungary	0.0038	0.0008	0.0030	0.0033	-0.0010	0.0043
Ireland	0.0178	0.0074	0.0104	0.0093	0.0029	0.0064
Italy	0.0212	-0.0069	0.0281	0.0111	-0.0130	0.0240
Latvia	0.0036	0.0005	0.0031	0.0044	0.0006	0.0038
Lithuania	0.0024	0.0003	0.0021	0.0030	-0.0001	0.0031
Luxembourg [1]	-	0.0003	-	-	0.0002	-
Malta [1]	-	0.0000	-	-	0.0000	-
Netherlands	0.0380	0.0159	0.0220	0.0200	0.0034	0.0166
Poland	0.0045	0.0016	0.0028	0.0053	0.0017	0.0036
Portugal	0.0123	-0.0054	0.0178	0.0023	-0.0060	0.0083
Romania	0.0021	0.0004	0.0017	0.0016	0.0003	0.0013
Slovak Republic	0.0065	0.0025	0.0041	0.0087	-0.0017	0.0105
Slovenia	0.0068	-0.0015	0.0083	0.0054	-0.0027	0.0081
Spain	0.0132	-0.0049	0.0181	0.0035	-0.0121	0.0156
Sweden [1]	-	0.0000	-	-	0.0000	-
United Kingdom [1]	0.0577	0.0240	0.0305	0.0507	0.0281	0.0147
European Union-27 [2]	*0.0139*	*0.0016*	*0.0123*	*0.0102*	*-0.0015*	*0.0116*

[1] *Due to problems of infeasibility averages for eco-performance change and technical change are not computed for Luxembourg, Malta and Sweden; furthermore, in the case of the United Kingdom, averages are computed using 17 year-to-year growth rates in the cases of proportional GHG, N_2O and CH4, and 15 for CO_2.*

[2] *Averages for the European Union-27 have been computed excluding Luxembourg, Malta and Sweden and the United Kingdom.*

Table 3
Eco-efficiency in GHG emissions in the European Union-27

	Average 1990-92				Average 2008-10			
	GHG	CO_2	N_2O	CH_4	GHG	CO_2	N_2O	CH_4
Austria	0.090	0.267	0.128	0.336	0.154	0.474	0.213	0.317
Belgium	0.305	0.545	0.532	0.317	0.314	0.612	0.457	0.329
Bulgaria	0.942	0.944	0.972	0.974	0.912	0.933	0.955	0.961
Cyprus	0.466	0.646	0.702	0.809	0.469	0.753	0.668	0.906
Czech Republic	0.842	0.903	0.909	0.890	0.795	0.886	0.885	0.864
Denmark	0.266	0.375	0.546	0.268	0.360	0.419	0.446	0.463
Estonia	0.891	0.951	0.954	0.892	0.848	0.916	0.917	0.863
Finland	0.443	0.511	0.601	0.472	0.406	0.585	0.583	0.423
France	0.223	0.223	0.538	0.378	0.354	0.354	0.514	0.587
Germany	0.307	0.535	0.463	0.443	0.264	0.579	0.403	0.284
Greece	0.602	0.654	0.803	0.658	0.569	0.744	0.763	0.725
Hungary	0.812	0.826	0.914	0.871	0.809	0.818	0.909	0.886
Ireland	0.564	0.564	0.857	0.873	0.509	0.509	0.701	0.817
Italy	0.092	0.284	0.137	0.220	0.209	0.556	0.303	0.482
Latvia	0.856	0.856	0.951	0.914	0.748	0.748	0.922	0.884
Lithuania	0.869	0.869	0.952	0.907	0.780	0.780	0.952	0.904
Luxembourg	0.001	0.209	0.002	0.002	0.000	0.000	0.000	0.000
Malta	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Netherlands	0.435	0.490	0.580	0.606	0.161	0.466	0.248	0.557
Poland	0.873	0.912	0.931	0.911	0.820	0.874	0.907	0.882
Portugal	0.356	0.446	0.483	0.694	0.462	0.628	0.619	0.819
Romania	0.910	0.929	0.954	0.962	0.888	0.897	0.946	0.958
Slovak Republic	0.792	0.870	0.905	0.798	0.730	0.802	0.862	0.824
Slovenia	0.552	0.686	0.757	0.744	0.547	0.734	0.749	0.779
Spain	0.348	0.448	0.475	0.406	0.433	0.603	0.578	0.649
Sweden	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
United Kingdom	0.348	0.462	0.480	0.596	0.012	0.051	0.017	0.109
Average EU-27 [1]	*0.488*	*0.571*	*0.612*	*0.590*	*0.465*	*0.582*	*0.575*	*0.603*

[1] *Computed as the arithmetic mean of all countries in the EU-27.*