61

Economie et Statistiques
Working papers du STATEC

Octobre 2012

Auteur : Chiara Peroni
STATEC

Environmental efficiency indices: towards a new approach to green-growth accounting

Abstract

This article analyses the link between environmental and productive efficiency using a non-parametric production frontier approach (DEA). A EU-US frontier of environmentally efficient countries, and comparative efficiency scores, are computed using data from the UN Framework Convention on Climate Change. Efficiency scores are interpreted as enhanced measures of carbon intensity and countries are ranked according to their ability to increase production while reducing pollutants. Results show that productive efficiency is considerably lowered when environmental degradation is taken into account. Only two (Luxembourg and Sweden) out of 16 countries are environmentally efficient. Malmquist indices, however, show that environmental performances improved over the period in nearly all countries. Furthermore, the net effect of recessions on environmental performance is negative. A decomposition of carbon intensity, which links emission performance to technical progress, is also presented; this highlights the positive contribution of technical change on the reduction in carbon intensity and the relevance of energy efficiency.

KEY WORDS: Carbon intensity; DEA; Malmquist index; decomposition; Kuznets curve.

I wish to thank Serge Allegrezza, Guy Schuller, Anne Dubrocard, and STATEC Scientific Committe members, in particular profs. Lionel Fontagné and Luisito Bertinelli, for their comments. Thanks are due to Charles-Henri DiMaria and Olivier Thunus for help and advice, Natasha Wagner and seminar participants at Statec and EAERE2012.

Economic growth is perceived to generate environmental degradation. The effect of industrial activities on the environment and to the consequences of climate change on human welfare is generating widespread concerns. The link between climate change and human activity has been established by a comprehensive study conducted by the Berkeley Earth group, which confirms previous studies by the MET office/CRU-UEA and NASA.[1] The idea that production processes and economic policies should take into account sustainability issues is the focus of demand from (and to) policy makers. At the core of environmental policy guidelines of international organisations (UN, OECD) is the principle of prevention, which states that technology should aim to reduce pollution. In addition, international agreements (the 1997 Kyoto protocol), which set targets to reduce emissions of greenhouse-gases, envisage mechanisms to develop markets for tradable emission quotas. One such scheme, the European Union Emissions Trading Scheme, enables less polluting companies to sell their surplus of emission allowances to bigger polluters (Directive 2003/87/EC). In this context, it is crucial to measure how production units (firms, industries, countries) are successful in reducing pollutants.

This study measures environmental efficiency of countries using a DEA-frontier approach. Environmental efficiency is defined as the ability of producing more while polluting less. Pollutants are incorporated into production technologies as undesirable outputs (Fare et al., 1989). The technology obeys two crucial assumptions: 1) the elimination of bad outputs is costly (weak disposability); 2) returns to scales are variable. Environmental efficiency scores are practically computed by Data Envelopment Analysis (DEA — Charnes et al., 1978). DEA compares each economic unit to a best practice frontier to identify those units that produce lower levels of pollutants *and* greater amount of desirable productions.

Advantages of DEA measures of environmental efficiency on standard economic approaches have already been pointed out in the literature. (This adds to standard DEA advantages, such as minimal assumptions, mild data requirements and flexible application.) This framework does not require observations on undesirable outputs' prices (Fare et al., 1989). As a result, it avoids placing a monetary weight on environmental impacts, which is regarded as highly controversial. Furthermore, DEA computes a single aggregate index which does not require weighting of environmental impacts (Tyteca, 1996, 1997).

Here, it is argued that DEA-based indicators of environmental performance offer more robust measures of environmental efficiency than standard indicators. The latter often capture economic cycles and changes in the structure of economies rather than genuine improvements in environmental efficiency which, for example, stems from the adoption of greener technologies. Thus, the goal of this study is to estimate an enhanced measure of carbon intensity at country level. The most recent data on greenhouse-gases (GHGs) emissions from the United Nations Framework Convention on Climate Change (UNFCC) are used to construct a DEA frontier and an environmental efficiency index (EPI) for Western European Countries and the US. Malmquist indices of the EPIs are also computed, capturing how environmental performance evolves over time. This is done under a Variable Returns to Scale DEA technology (Zhou et al., 2008). The environmental efficiency scores are compared to pure economic efficiencies to test the existence of Environmental Kuznet Curves (EKCs), a popular — and much questioned — framework to analyse the relation of environmental degradation to economic growth. Furthermore, it is shown that the frontier approach can lead to a green growth accounting framework, which establishes a link between productive efficiency, technical progress

[1] http://berkeleyearth.org.

and measures of environmental performance. Computations are carried out using SAS routines first developed by DiMaria and Ciccone (2008).

Related studies are those of Zaim and Taskin (2000a), Fare et al. (2004), Zaim and Taskin (2000b), Zhou et al. (2008), and Zhou et al. (2010), which assess eco-environmental performance at country or regional level. These studies, which use mainly OECD and International Energy Agency (IEA) data, differ in sample periods, countries analysed and measures of bad outputs and inputs. Zaim and Taskin (2000a) compare indices obtained under weak and strong disposability for OECD countries from 1980 to 1990, with the aim of computing output losses generated by environmental policies constraints. The same authors (Zaim and Taskin, 2000b) use environmental efficiency scores to test for the existence of EKC within a standard regression framework. Fare et al. (2004) compare production of desirable output (GDP) to multiple undesirable outputs for a group of industrialised countries in 1990. These authors propose to compute separate indices, to quantify by how much it is possible to increase good output given bad output and inputs use, and by how much it is possible to expand bad output while keeping good output and inputs fixed. The ratio of these two quantities gives the environmental efficiency index. Zhou et al. (2008) compares the environmental performances of 8 world regions (OECD, non-OECD Europe, Africa, etc..) in 2002 using a DEA VRS technology. The obtained efficiency scores amount to an estimate of ratios of the reciprocal of carbon intensity (CO2/GDP) that takes into account the carbon factor (emissions/energy). Results show that carbon intensity is correlated to environmental performances. Zhou et al. (2010) extend this framework to compute Malmquist indices for a panel of 18 (top emitters) countries from 1995 to 2004. They found that environmental performance improved by 24%, due mainly to technical progress.

The article has the following structure. Section 1 outlines the methodological framework underlying the empirical analysis of this study. Section 2 describes the data used in the analysis and presents some widely used indicators of carbon emission performance. Section 3 presents environmental efficiency indices for a group of EU member states and the US, and compares them to pure productive efficiency index to test for the existence of a DEA EKC. Section 4 presents Malmquist indices of environmental performance and discusses a framework for environmental growth accounting. Section 5 gives concluding remarks and directions for future research.

1 The environmental efficiency index

The evaluation of countries' environmental performance uses a framework originally developed by Farrell (1957) for measuring the *productive efficiency* of economic units. In this framework, production sets and distance functions generalise the idea of production function. Production sets define technology in terms of feasible input/output sets; distance functions measure operating efficiency by comparing observed output to the boundary of the production set (the frontier). Distance functions offer a mean of comparing different units in terms of their position to the frontier, and to study the evolution of the units' performance when the structure of technology changes.

Assume that each economic unit — or Decision Making Unit (DMU) — produces a single output, denoted by y, using a vector of input $\mathbf{x} \in R^N_+$.[2] Formally, the **production possibility set** in period t is as follows:

$$S_t = \{(\mathbf{x}_t, y_t) : \mathbf{x}_t \text{ can produce } y_t\}; \tag{1}$$

Here, The set S represents all feasible input/output vectors $(\mathbf{x}, y)$ such that using $\mathbf{x}$ one can produce y. The boundary of S, the *frontier*, gives the maximum output obtainable from a given amount of inputs use. DMUs operating on the frontier are said to be efficient because they make full use of the inputs. The **output distance function** describes all operating DMUs in terms of their *relative* position to the frontier:

$$D^t(\mathbf{x}_t, y_t) = inf\{\theta : (x_t, \frac{y_t}{\theta}) \in S_t,\ \theta \geq 0\}; \tag{2}$$

Here, D gives the smallest (*infimum*) of the set of real numbers θ, where θ is such that the input/output combination $(\mathbf{x}_t, y_t)$ belongs to the production possibility set S_t.[3] $D^t(\mathbf{x}_t, y_t)$ measures the reciprocal of the required expansion in output given inputs $\mathbf{x}_t$ to attain the frontier defined by S_t. D takes the value of 1 for those DMUs on the frontier and less than 1 for those DMUs below the frontier. Larger values of D are associated to units closer to the frontier.

The DEA method (Charnes et al., 1978) provides a way of computing distance functions. DEA selects the most efficient unit for each observed combination of input (that is, the unit which produces the highest amount of output), and constructs the frontier by joining the set of points represented by those efficient units. This is done by solving the following linear programming problem (LP):

$$\begin{array}{lll} max_{\lambda,\Phi} & \lambda_0 & \\ s.t. & \sum_{j=1}^{J} x_{ij}\phi_j \leq x_{i0}, & \text{for every} \quad i \\ & -\sum_{j=1}^{J} y_j\phi_j + \lambda_0 y_0 \leq 0 & \\ & \Phi, \lambda \geq 0 & \end{array} \tag{3}$$

Here, the subscripts i and j index, respectively, inputs and DMUs; Φ is a vector (J x 1) of coefficients for the DMUs; λ is a score to be maximized. (The subscript 0 indicates that the problem is solved with respect to a reference DMUs.) Intuitively, the LP problem above seeks the biggest possible expansion of the output of DMU_0, while remaining within the feasibility

[2]Economic units, object of the efficiency analysis, may indicate firms, industries, regions, countries.
[3]The term *infimum* denotes the lowest bound of the set θ.

set. The solution gives a score for each DMU, λ_0^*; the efficiency measure for DMU_0 is equal to the reciprocal of such score: $E_0 = 1/\lambda_0^*$. The DMUs with a score equal to 1 will define the efficient frontier.[4]

The method outlined above can be extended to incorporate pollution as an undesirable output of production technologies. Fare et al. (1989) first extended Farrell's approach to productive efficiency when production yields outputs that are undesirable and others that are not. In this context, efficiency is measured by the amount by which it is possible to increase output and, at the same time, reduce the amount of pollutants at a given level of inputs use. The best practice frontier identifies those units producing the lowest level of pollutants together with the greatest amount of desirable production. According to Fare et al. (1989), an environmental feasible technology set satisfies the following assumptions:

$$1.\ if\ (x, y, u) \in S\ and\ 0 \leq \theta \leq 1\ then\ (x, \theta y, \theta u) \in S$$
$$2.\ if\ (x, y, u) \in S\ and\ u = 0\ then\ y = 0$$

(Here, u denotes the undesirable output.) The first assumption, *weak disposability*, implies that the disposal of undesirable output is costly and that it is not possible to decrease the production of the bad output without decreasing the production of the good output (or decreasing inputs' use) (Fare and Grosskopf, 2004; Fare et al., 1994a). The second assumptions, the *pollution problem*, states that it is not possible to stop production of bad outputs unless production is stopped altogether. Fare et al. (1989) formulate a DEA problem which permits the expansion of output and the simultaneous contraction of undesirable output, within the constraints imposed by inputs' use and technology, as follows:

$$\begin{aligned} max_{\lambda,\Phi} \quad & \lambda_0 \\ s.t. \quad & \textstyle\sum_{j=1}^{J} x_{ij}\phi_j \leq x_{i0}, \quad \text{for every} \quad i \\ & -\textstyle\sum_{j=1}^{J} y_j\phi_j + \lambda_0 y_0 \leq 0 \\ & -\textstyle\sum_{j=1}^{J} u_j\phi_j + \lambda_0^{-1} u_0 = 0 \\ & \Phi, \lambda \geq 0 \end{aligned} \tag{4}$$

(Here, the equality sign in the constraint for the undesirable output guarantees that weak disposability is satisfied.)[5] The resulting optimal score give a measure of efficiency that takes into account the presence of environmental constraints and pollution, an environmental performance indicator (EPI). In the spirit of Fare et al. (1989), Zhou et al. (2008) extend the problem of eq. 4 to consider the computation of environmental efficiency scores under different assumptions on returns to scale, namely non-increasing returns to scale (NIRS) and

[4]The formulation of problem 3, also referred to as the envelopment form, represents the dual of a non-linear fractional problem. Charnes et al. (1978) shows how the original problem, which minimises a ratio of input on output, can be transformed into a linear score problem. This clarifies the link between the linear program and the measurement of productive efficiency. The score formulation reduces the dimensionality of the problem as the number of constraints is equal to I (number of inputs) rather than J (number of DMU). The optimisation problem presented here is an output-oriented version, but it is also possible to formulate the problem as an input-oriented one. In the latter case, we seek the biggest possible reduction in inputs' use, while keeping output levels constant.

[5]Alternative formulations of the DEA environmental problem are possible. One can see Fare et al. (1989, 2004) and references therein. Furthermore, the problem above of eq 4 is a non-linear programming (NLP) one. Several ways have been proposed to overcome this difficulty: Fare et al. (1989)linearise the constraint on the undesirable output, while Fare et al. (2004) adopt directional distance functions.

variable returns to scale (VRS). The LP problem under environmental constraint and VRS is as follows:

$$\begin{aligned} min_{\lambda,\Phi} \quad & \frac{\lambda_0}{\theta_0} \\ s.t. \quad & -\sum_{j=1}^{J} x_{ij}\phi_j + x_{i0} \geq 0, \quad \text{for every} \quad i \\ & \sum_{j=1}^{J} y_j\phi_j + \theta_0 y_0 \geq 0 \\ & \sum_{j=1}^{J} u_j\phi_j - \lambda_0 u_0 = 0 \\ & \sum_{j=1}^{J} \phi_j = 1 \\ & \Phi \geq 0 \end{aligned} \tag{5}$$

This problem seeks to minimize the ratio of undesirable inputs to desirable output. The constraint that the DMU's coefficients' sum should be equal to one imposes VRS on the technology set. (Note that, once again, this is a non-linear problem, for which Zhou et al., 2008, give a linearised formulation.).

The direct approach outlined above allows us to construct an aggregated environmental performance index (EPI) at country level, which grades countries according to their ability to increase output and decrease desirable output. The EPI is computed at any given point in time. The next section considers the measurement of environmental efficiency performances in a dynamic context.

1.1 Malmquist indices of environmental performance

Caves et al. (1982) first proposed the use of the Malmquist index to measure productivity changes. Given two time period t and $t+1$, the Malmquist index of productivity is defined as follows:

$$M^{t,t+1} = \left[\left(\frac{D^t(x^{t+1}, y^{t+1})}{D^t(x^t, y^t)} \right) \left(\frac{D^{t+1}(x^{t+1}, y^{t+1})}{D^{t+1}(x^t, y^t)} \right) \right]^{\frac{1}{2}}; \tag{6}$$

The index is given by the ratio of distance functions obtained by comparing output to inputs in time t and time $t+1$ using a given reference technology. (Here, the geometric averages of indices obtained using both S^t and S^{t+1} production sets avoids the arbitrary choice of a reference technology.) In other words, equation 6 considers how much a unit could produce using the inputs available in $t+1$, if it used the technology at time t, and how much a unit could produce using the inputs available in t, if it used the technology available in $t+1$.[6] Fare et al. (1994b) showed that equation 6 can be decomposed into efficiency gains and technical progress, as follows:

$$M^{t,t+1} = \underbrace{\frac{D^{t+1}(x^{t+1}, y^{t+1})}{D^t(x^t, y^t)}}_{efficiency\ gains} \underbrace{\left[\left(\frac{D^t(x^{t+1}, y^{t+1})}{D^{t+1}(x^{t+1}, y^{t+1})} \right) \left(\frac{D^t(x^t, y^t)}{D^{t+1}(x^t, y^t)} \right) \right]^{\frac{1}{2}}}_{technical\ progress}; \tag{7}$$

Here, the first term — a ratio of distances to the frontiers in period t and $t+1$ — represents the pure change in efficiency. The second term, which measures the shifts in the frontier, provides a measure of technical change.[7] This is achieved by comparing, for the same level

[6] One can see that practical implementation requires the solution of 4 LP problems.
[7] In this framework, technical change means an expansion of the production possibility set.

of inputs (in t or $t+1$), the distance functions obtained under the technology in t and $t+1$. (Once again, we have a geometric mean of ratios obtained under the technology in t and $t+1$.)

The Malmquist index has been widely applied in the analysis of productivity and total factor productivity changes. In this article, Malmquist indices are computed using distance functions obtained from a VRS environmental DEA technology, which replace standard output distance functions. These give changes in environmental performances over time.

2 The data

This analysis uses data on greenhouse gases emissions and on the economic performances of 15 Western European (EU member) countries and the US from 1995 to 2009. (The analysis is restricted to this group of countries for reasons of data availability and reliability.)[8] Employment and GDP data are gathered from Eurostat and Statec. Energy consumption is sourced from Eurostat (Energy and Environment dataset). The US energy consumption comes from the EIA (Energy Information Administration).

Data on carbon dioxide (CO2), nitrous oxide (N2O), and total greenhouse-gases (GHGs) emissions are from the UNFCC database. In the UN database, emissions are expressed in CO2 equivalent, which permits to aggregate data and obtain a global measure of GHGs emission. The series range from 1995 to 2009, the last available observation at the time of writing.[9] N2O is also considered because this gas is an often overlooked major air pollutant.[10] The remaining of this section presents some widely used indicators of environmental performance based on this data. Summary statistics for the main variables are reported in Table 9 in the Appendix to this article.

Figure 1 shows that the US were responsible for the largest share of CO2 emissions in 2009, accounting for about the 64% of total CO2 emissions in our sample. Among european countries, the biggest polluters were Germany (about 9% of total emissions), followed by the UK (5.6%), Italy (about 5%), France (4.4%) and Spain (3.5%). All other countries contributed for less than 2% each. (Pie charts for GHGs are not reported, as figure are very close to those in the CO2 graph.) Things look different when considering shares in N2O emissions, as shown in figure 2. The US and the EU equally shared the N2O emissions; among EU countries, Germany and France were the biggest polluters, with respective shares of 12% and 11%. The UK, Italy, and Spain accounted for, respectively, 6%, 5% and 4.6% of total emissions. Over the period analysed, the US share of emissions increased from 62% recorded in 1995 to the 64% in 2009 for CO2, and from 47% to 51% for N2O.

To account for countries' size and economic activity, the following considers emissions per capita and per unit of Gross Domestic Product (GDP). In particular, the ratio of GHGs to GDP gives the carbon intensity, a widely used environmental performance indicators (Ang,

[8]The countries in this analysis account for a share of 61% of the GHG emissions in the UNFCC database. China and India are not available in this database.

[9]Data were downloaded from the UNFCC website http://unfccc.int/2860.php on 15/03/2012.

[10]While CO2 emissions are the largest contributors to total GHGs emissions, N20 has been found the largest contributor to the depletion of the atmospheric ozone layer (see Ravishankara et al., 2009, and reference therein). Its status as a dangerous air pollutant has been confirmed in the 2007 IPCC Fourth Assessment Report (AR4), which established that the N2O global warming potential (GWP) is 300-fold compared to the CO2's one. (Working Group 1, Chapter 2 "Changes in Atmospheric Constituents and in Radiative Forcing", available on http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter2.pdf).

1999). Table 1 gives average (yearly) growth rates of emissions — per capita and per unit of GDP — and the carbon factor (energy/GDP). It also gives GDP per worker growth and capital deepening rates. All countries experienced negative growth in emissions per capita from 1995 to 2009. Luxembourg, UK and Ireland GHGs emissions contracted by 2.4% per year. Substantial decrease rates were also recorded for Belgium, Denmark, Netherlands and Sweden. The emissions of the other EU biggest economies (Italy, Spain, Germany, and France) decreased at rates comprised between 1 and 2%. Portugal and Greece had the lowest decline in emissions, which was also slow in Austria and the US. The evolution of CO2 followed closely GHGs, as expected, whereas N20 contracted even more markedly. Carbon intensity also decreased substantially in all countries, with the exception of Greece. Interestingly, the energy factor decreased in a majority of countries, but at lower rates than emissions; it increased in Italy, Spain, Portugal and Greece.

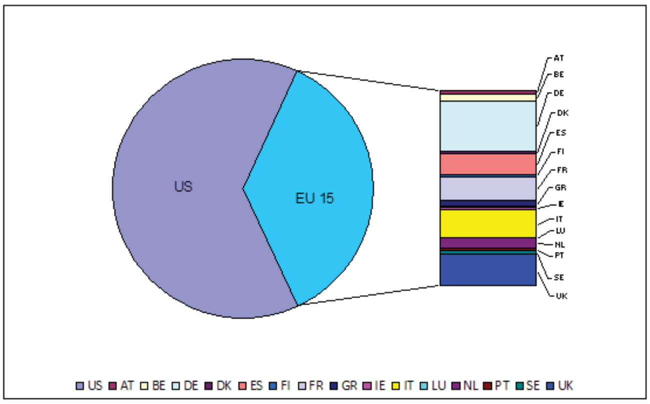

Figure 1: CO2 emissions for the US and EU in 2009 (% share).(Source: UNFCC).

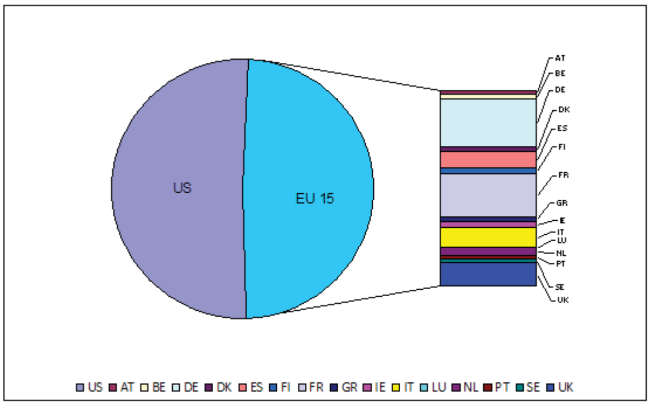

Figure 2: N2O emissions for the US and EU in 2009 (% share).(Source: UNFCC).

Figure 3 and 4 present, respectively, the evolution over time of countries' GHG emissions per worker and of carbon intensity. The graph compare beginning-of-period data (1994) to end-of-period data (2009), including observations for 2004, the last available year in the study by DiMaria and Ciccone (2008). They reveal the generalised reductions in emissions per capita and carbon intensity. One can see that, in 1995, the US, Luxembourg and Ireland were the countries with the highest level of emissions per capita (> 30 tonnes), followed by Belgium and Finland. The countries' ranking did not change over the period, but the worst polluters managed to substantially reduce their emissions per capita (with the exception of the US were the decline was moderate). In Greece, Portugal and Austria, emissions recorded in 2004 were higher than in 1995, but fell in 2009 (possibly due to the effect of the financial crisis). The country ranking for carbon intensity is different from the one suggested by the emissions per capita data. In 1995, the US were the worst performers, followed by Ireland, Finland and Belgium. Luxembourg, the Netherlands, Germany and Denmark also had high levels of carbon intensity. In 2009, the relative positions had changed, with the US still the worst performer but this time round followed by Greece, Ireland, Finland and Belgium and.

Table 1: **Environmental performance indicators: yearly % changes (1995-2009)**

Country	GHG	CO2	N2O	GHG/GDP	GDP/L	K/L	nrg/GDP
AT	-0.898	-0.533	-2.315	-1.895	1.017	2.937	-0.458
BE	-2.295	-1.923	-3.939	-2.675	0.390	1.578	-1.334
DE	-1.857	-1.634	-1.934	-3.177	1.363	3.438	-2.050
DK	-2.102	-2.192	-3.134	-2.428	0.334	2.854	-0.967
ES	-1.357	-1.339	-2.507	-0.956	-0.405	2.688	0.307
FI	-1.743	-1.588	-2.453	-3.004	1.300	1.674	-1.864
FR	-1.426	-1.225	-3.491	-2.236	0.828	2.767	-1.157
GR	-0.164	0.314	-2.792	-0.016	-0.148	1.777	1.069
IE	-2.414	-1.566	-4.561	-3.070	0.677	3.910	-0.770
IT	-1.452	-1.385	-3.114	-0.527	-0.930	2.522	0.414
LU	-2.440	-2.343	-3.843	-2.328	-0.115	0.346	-1.522
NL	-2.173	-1.400	-6.344	-2.780	0.624	2.000	-1.627
PT	-0.212	-0.253	-2.138	-0.695	0.486	5.246	0.826
SE	-2.076	-2.176	-1.652	-3.277	1.242	2.124	-2.513
UK	-2.401	-1.782	-4.242	-2.835	0.446	2.382	-1.520
US	-0.698	-0.673	-1.922	-1.473	0.786	2.792	-1.291
EU15	-1.751	-1.482	-3.152	-2.456	0.722		-1.300

Legend: Data are average yearly changes (geometric means); GDP/L and K/L denote, respectively, GDP per worker and capital per worker; nrg/GDP is energy consumption over GDP. (Sources: UNFCC, Eurostat.)

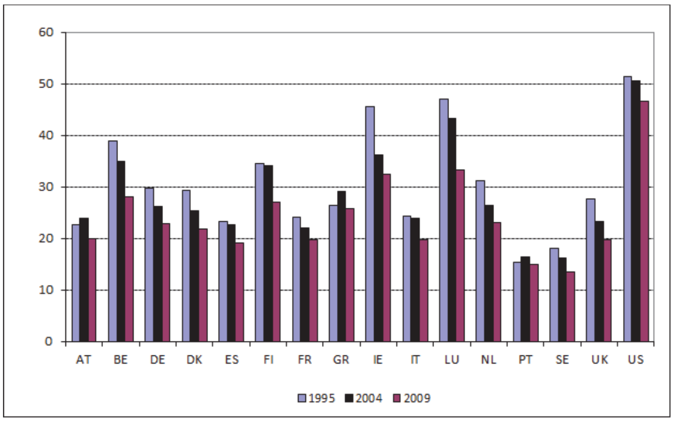

Figure 3: Evolution of GHGs emissions per worker, 1995-2009.(Source: UNFCC, Eurostat).

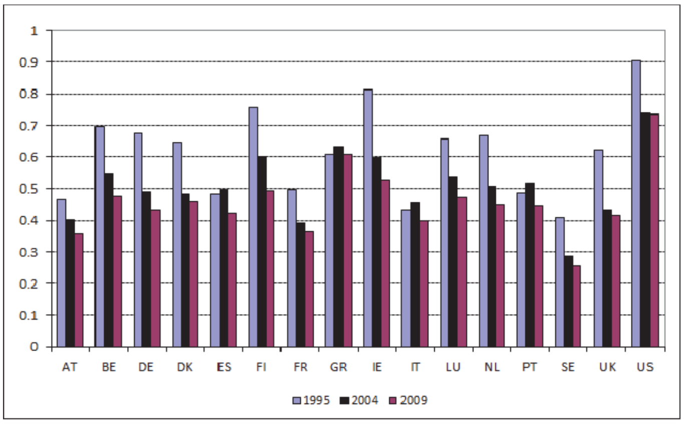

Figure 4: Evolution of Carbon intensity, 1995-2009.(Source: UNFCC, Eurostat).

To analyse the evolution of countries' environmental performance with respect to Luxembourg, the worst EU performers in terms of emissions per capita, table 2 presents carbon intensity series, normalised so that Luxembourg data is equal to 1 in each period. One can see that, overall, Luxembourg was decisively outperformed by several countries, namely Austria, France, Italy, Spain, Sweden and the UK. (These countries have period averages below 1.) Another group of countries, which includes the US, Ireland, Finland and Belgium, performed worse than Luxembourg. Denmark, Germany and the Netherlands data were close to Luxembourg. Comparing 2009 to 1995, one observes that the ranking of Luxembourg deteriorated slightly, from the 7t to th 6th position. Several countries sees a deterioration in their emisison level with respect to Luxembourg: Austria, Spain, Greece, Portugal, Italy and the US.

Table 2: **Carbon intensity: Luxembourg comparative performance**

Country	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
AT	0.71	0.73	0.79	0.89	0.88	0.83	0.85	0.82	0.83	0.75	0.76	0.76	0.80	0.80	0.76
BE	1.06	1.09	1.11	1.37	1.31	1.23	1.17	1.10	1.09	1.02	0.98	1.00	1.05	1.08	1.01
DE	1.03	1.04	1.11	1.26	1.23	1.18	1.12	1.07	1.01	0.91	0.86	0.89	0.92	0.93	0.91
DK	0.99	1.13	1.10	1.21	1.20	1.08	1.07	1.01	1.07	0.91	0.85	0.99	1.00	0.98	0.97
ES	0.74	0.72	0.83	0.98	1.07	1.06	1.00	0.99	0.97	0.93	0.94	0.94	1.02	0.97	0.90
FI	1.15	1.22	1.26	1.37	1.36	1.25	1.29	1.27	1.34	1.12	0.93	1.12	1.14	1.03	1.05
FR	0.76	0.78	0.83	0.98	0.95	0.89	0.83	0.79	0.79	0.73	0.71	0.73	0.77	0.79	0.77
GR	0.93	0.99	1.17	1.48	1.53	1.50	1.40	1.30	1.28	1.18	1.21	1.21	1.35	1.31	1.29
IE	1.24	1.17	1.25	1.49	1.52	1.48	1.44	1.32	1.24	1.11	1.09	1.10	1.12	1.19	1.11
IT	0.65	0.66	0.75	0.88	0.93	0.91	0.86	0.88	0.89	0.85	0.84	0.86	0.90	0.89	0.84
LU	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
NL	1.02	1.02	1.07	1.22	1.15	1.09	1.06	1.03	1.03	0.94	0.89	0.90	0.94	0.95	0.95
PT	0.74	0.72	0.82	1.02	1.14	1.07	1.04	1.07	0.98	0.96	0.93	0.93	0.98	0.98	0.94
SE	0.62	0.64	0.66	0.77	0.72	0.67	0.66	0.64	0.61	0.53	0.51	0.52	0.54	0.54	0.54
UK	0.94	0.96	0.99	1.15	1.12	1.05	0.98	0.92	0.89	0.81	0.79	0.83	0.91	0.91	0.88
US	1.38	1.39	1.51	1.73	1.73	1.70	1.60	1.56	1.48	1.38	1.34	1.43	1.58	1.61	1.56

Legend: Evolution of carbon intensity in comparison to Luxembourg.
(Sources: UNFCC, Eurostat.)

This data raise the issue of whether common indicators of environmental degradation are capable of capturing genuine improvements in environmental performances. Such measures, generally expressed as ratios of emissions to pure economic indicators (employment and output), may reflect cycles or changes in countries' economic structure rather than the adoption of environmental technologies or increases in energy efficiency. In particular, while emissions per capita reflect mainly the evolution in the numerator, carbon intensity figures reflect both changes in output and in emissions.[11]

Figure 5 plots rates of growth of GDP per capita versus GHG emissions per capita (growth rates are period averages). One observes several group of countries characterised by different relations between income and emissions, and two possible outliers, Spain (ES) and Italy (IT), characterised by moderate decline in emissions and negative GDP growth.[12] This suggests that the decline in carbon intensity was the consequence of increases in GDP in Germany, Finland and Sweden. It reflected lower levels of emissions in Luxembourg, Denmark, Belgium and Ireland, which was the likely consequence of the transformation of these countries into service-intensive economies. In Austria, the US and Portugal GDP growth compensates, on average, emissions decline.

The descriptive analysis of this section suggests that the relation income-pollution is far from being simple, and that standard indicators may not be adequate in capturing countries' environmental efficiency. This may explain the contradiction between the perceived increase in environmental degradation and improvements in emissions indicators, at least for western Europe and the US. The remaining of this article attempts to identify better measures of environmental performance and reviews the evidence on their link with economic indicators.

[11]In western Europe, employment figures were pretty stable in the last decade. One should note, however, that employment growth was sustained in Ireland and Luxembourg, which may partly explain the decline in emissions per capita in those two countries. On the evolution of inputs and output indicators for the same group of countries analysed in this paper, one can see Peroni (2012).

[12]A cluster analysis, conducted on several countries characteristics, does not allow to shed further light on countries' groups and variations. In particular, we did not find any link between degrees of openness of the economies and environmental performance measures.

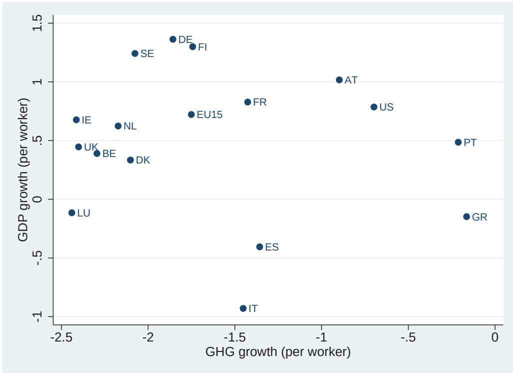

Figure 5: Scatterplot of income growth vs GHG emissions growth (period averages, per capita). (Source: UNFCC, Eurostat).

3 Eco-environmental performance

This section presents an aggregate environmental performance index (EPI), for the 16 countries in our dataset from 1995 to 2009, which provides a ranking of countries according to their ability to increase output and decrease the undesirable output. The index is the mixed environmental performance index (MEI) proposed by Zhou et al. (2008). The underlying environmental DEA technology assumes weak disposability of the undesirable output (Fare et al., 1989) and Variable Returns to Scale (VRS).

Table 3 lists the countries and displays their eco-environmental efficiency scores for selected years. (Full results are in the Appendix, Table 10.) The EPIs are obtained by solving the linear programming problem in equation 5. The optimisation problem compares the use of inputs to two categories of output, namely desirable (GDP) and undesirable output (GHG emissions), for each country and for each year. Inputs to production are labour, energy, and capital stock. Energy is included as many studies have concluded that it is a relevant input in efficiency analysis (see Chen and Yu, 2012, and references therein). The resulting score lie between zero and one (best performance), and their values indicate the factor by which a country can reduce emissions while simultaneously expanding its output and still remain within the feasible production set. For example, a score of 0.35 for the US (2009) means that this country could expand is production by an amount of 1/0.35 while decreasing by the same amount its emissions.

One can see that only Luxembourg and Sweden are fully efficient with respect to the US-EU frontier. On average, Greece and the US are the countries furthest away from the frontier. In practise, these countries could more than double their production while halving their emissions. Other countries which perform poorly are Belgium, Ireland, and Finland. In contrast, the countries on the frontier could improve their environmental performance only by improving their technology.

The EPI index is significantly negatively correlated with carbon intensity and emissions per worker indicators, as expected. (An increase in emissions per capita/unit of GDP signals a deterioration in environmental performance.)

Nearly all countries exhibit a deterioration in their performances over the period (eg they move further away from the frontier). The countries experiencing the biggest deterioration are

Spain, Italy and Portugal. This contrasts to the improvements in standard indicators of environmental performance presented in the previous section, and suggests that it is inappropriate to evaluate environmental performances only by looking at indicators such as carbon intensity or emissions per capita. Efficiency scores, however, are computed using cross-sectional data and they are better interpreted as static rankings. To overcome this limitation and study their evolution, the next section presents Malmquist indices of environmental performances.

Table 3: Eco-environmental performances (EPI)

Country	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	average
AT	0.91	0.82	0.79	0.79	0.75	0.73	0.69	0.70	0.69	0.69	0.73	0.75
BE	0.59	0.54	0.56	0.58	0.56	0.52	0.52	0.52	0.52	0.50	0.54	0.54
DE	0.61	0.57	0.58	0.60	0.60	0.59	0.60	0.59	0.58	0.58	0.60	0.59
DK	0.68	0.66	0.66	0.68	0.62	0.66	0.68	0.60	0.60	0.62	0.62	0.64
ES	0.84	0.63	0.66	0.65	0.63	0.57	0.55	0.56	0.53	0.56	0.61	0.62
FI	0.57	0.56	0.53	0.53	0.48	0.51	0.60	0.51	0.51	0.56	0.56	0.54
FR	0.82	0.75	0.79	0.81	0.77	0.73	0.72	0.72	0.70	0.68	0.71	0.74
GR	0.72	0.46	0.49	0.51	0.50	0.48	0.45	0.46	0.42	0.44	0.45	0.49
IE	0.60	0.51	0.51	0.55	0.56	0.57	0.56	0.56	0.56	0.53	0.58	0.55
IT	0.95	0.73	0.76	0.72	0.69	0.63	0.61	0.61	0.60	0.60	0.64	0.69
LU	1	1	1	1	1	1	1	1	1	1	1	1.00
NL	0.61	0.61	0.62	0.62	0.59	0.57	0.58	0.58	0.57	0.57	0.57	0.59
PT	0.91	0.65	0.66	0.63	0.65	0.60	0.60	0.61	0.59	0.59	0.62	0.65
SE	1	1	1	1	1	1	1	1	1	1	1	1.00
UK	0.66	0.63	0.67	0.69	0.68	0.66	0.65	0.63	0.59	0.59	0.62	0.64
US	0.45	0.39	0.41	0.41	0.41	0.39	0.38	0.37	0.34	0.34	0.35	0.38

4 Malmquist indices of environmental performance: towards a new framework for green growth accounting

Malmquist indices of environmental performances describe the evolution over time of the EPI computed in the previous section, and allow us to attribute improvements in environmental performances to increases in efficiency or improvements in technology. Changes in efficiency are usually interpreted as technological catch-up, as they measure how much a country approach the frontier, whereas changes in technology are viewed as the result of innovation efforts (Fare et al., 1994b) or investment in intangibles (Corrado et al., 2009). The indices are computed using equation 6, where distance functions are based on the DEA environmental technology described in Section 1.[13]

Here, Malmquist indices are computed under the assumptions of variable returns to scale (VRS), which makes results robust to change in the scale of technology both across countries and *over time*. ((A related study is the one of Zhou et al., 2010, who computed Malmquist indices of total factor carbon emission performance for the top 18 emitters from 1997 to 2004 using a CRS DEA technology.)

Table 4 presents the Malmquist indices for the 16 countries from 1996 to 2009. Tables 5 and 6 show, respectively, the efficiency change and the technological change components. (The index is not available for Luxembourg, due to feasibility issue often encountered in these problems.). The estimates indicate that all countries, with the exception of Spain, improved their emission performances. A group of countries (Austria, Ireland, Sweden and Germany) was characterised by growth rates higher than 3%. In some countries the volatility was also high.

One can see that nearly all countries were characterised by efficiency losses. Only Finland, Ireland and the US realised some efficiency gains. Countries which experienced the biggest efficiency losses were Italy, Spain, Portugal and Greece. Sweden and Luxembourg were on the frontier for the entire period. Thus, improvements in environmental performances were largely driven by technological progress, high enough to compensate efficiency losses. Environmental performances deteriorated in the years 2001 and 2008-2009, in correspondence of economic downturns. Once again, it is negative technical changes that drives this results.

Table 7 shows the cumulative Malmquist index and its components in 2009. This allows us to compare relative positions in the end of the period compared to the base year (1995). Several countries show large improvements, with Ireland, Austria, Sweden, Germany and Finland being the best performers. By contrast, Spain is worse off compared to 1995. Improvements in relative positions in Greece, Italy and Portugal are also modest.

[13]The computation of the Malmquist index involves the solution of 4 linear programming problems, 2 of which are mixed-period problems which often incur into feasibility issues. The linear programming problems are those in equation 5, corresponding to an environmental DEA technology.

Table 4: Malmquist indices of environmental performance 1995-2009

Country	1996	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	mean
AT	12.58	-3.36	4.86	1.50	-5.34	4.54	38.61	-10.66	5.24	-0.86	3.31	3.85
BE	-0.25	6.75	0.22	4.31	-3.01	0.38	2.94	5.22	5.57	-3.72	3.71	2.68
DE	1.31	4.19	-0.22	3.05	2.14	4.29	5.21	4.03	6.05	-1.27	-0.59	3.28
DK	-11.12	14.02	-4.38	5.11	-9.61	13.15	5.24	-7.91	-6.02	2.26	-1.75	1.98
ES	-3.12	1.30	1.25	-1.20	-2.00	-1.62	-1.64	7.02	1.50	5.55	4.38	-1.59
FI	-3.78	11.88	-8.54	0.67	-7.92	13.40	19.84	-13.66	6.21	7.84	0.31	3.28
FR	-0.30	7.07	2.13	2.99	-3.69	1.99	2.05	4.71	4.54	-2.84	-0.23	2.29
GR	-11.41	5.81	5.14	14.80	-7.65	14.94	-5.41	6.71	-1.31	3.34	-0.31	0.70
IE	6.35	2.37	-3.14	7.48	2.59	4.82	1.03	15.43	8.44	-5.87	10.97	3.96
IT	0.77	2.51	0.41	-4.59	-4.25	-1.38	0.56	5.08	4.85	0.27	2.94	1.45
LU												
NL	6.00	-5.12	-1.95	0.50	-3.54	3.40	5.14	5.69	5.66	-0.83	-3.66	2.91
PT	5.75	7.37	0.25	-4.56	4.96	-3.15	4.17	8.04	4.80	-0.74	1.90	1.31
SE	-1.01	10.19	-4.49	0.77	0.96	9.93	2.70	2.11	10.35	-0.58	-3.92	3.47
UK	0.83	6.61	1.78	4.83	-0.68	4.44	1.15	2.35	0.89	-1.30	0.97	2.91
US	1.60	1.48	1.06	0.96	1.34	1.52	1.58	0.73	-0.01	-2.00	-0.05	1.49

(Period averages are geometric means of yearly changes. Sources: author's calculations from UNFCC, Eurostat, Statec data.)

One problem with this analysis is that the computation of Malmquist indices under a VRS technology is not always possible, due to unfeasible LP cross-period problems. Empirically this is often observed for economic units on the frontier, as for Luxembourg in our analysis. Thus, we followed Hua et al. (2007) and Zhou et al. (2006) and attempted to solve this issue employing a slack-based method. Results were not satisfactory, and this is left for future research.

Table 5: Efficiency changes 1995-2009

Country	1996	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	mean
AT	0.25	-18.00	-4.04	0.86	-6.09	-2.12	37.07	-29.59	-2.22	-0.44	6.84	-1.51
BE	0.56	-1.65	3.88	3.49	-3.98	-6.59	-0.13	0.28	-1.64	-2.99	7.44	-0.64
DE	0.52	1.63	-0.63	-21.95	1.12	-2.99	2.02	-1.01	-1.39	-0.62	3.19	-0.44
DK	-11.47	6.29	3.39	-12.35	-9.62	33.57	-16.89	-12.93	0.92	2.72	1.19	-0.71
ES	0.00	-6.83	4.82	-2.01	-2.98	-8.49	-4.62	1.83	-5.62	6.25	8.35	-3.52
FI	-3.40	1.67	-2.89	-4.93	-4.93	8.49	19.40	-16.70	-0.26	9.28	2.68	0.46
FR	-1.08	-1.52	5.72	2.14	-4.65	-5.13	-1.05	-0.37	-2.80	-2.19	3.57	-1.40
GR	-26.73	-3.52	14.52	9.97	-1.15	13.27	-42.12	1.14	-8.47	3.78	43.20	-3.32
IE	6.66	-3.90	0.78	9.02	5.08	4.49	-7.45	-1.52	0.07	-5.44	37.05	1.32
IT	0.00	-5.71	3.95	-5.37	-5.20	-8.27	-2.49	-0.02	-2.51	0.94	6.86	-3.09
LU	0	0	0	0	0	0	0	0	0	0	0	0
NL	-19.59	-21.85	1.50	-0.33	-4.50	-3.82	1.94	0.56	-1.76	-0.16	0.01	-2.22
PT	5.42	-0.55	7.81	-20.30	4.58	15.95	-21.19	2.31	-2.91	-0.31	5.14	-2.75
SE	0	0	0	0	0	0	0	0	0	0	0	0
UK	0.08	-1.94	5.36	3.96	-1.67	-2.85	-1.92	-2.62	-6.19	-0.65	4.81	-0.80
US	0.80	-1.01	0.64	5.81	5.84	2.95	1.01	-4.13	-4.64	-2.27	-2.91	0.96

(Period averages are geometric means of yearly changes. Sources: author's calculations from UNFCC, Eurostat, Statec data.)

Table 6: Technological changes 1995-2009

Country	1996	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	mean
AT	12.30	17.85	9.28	0.63	0.80	6.80	1.12	26.87	7.62	-0.42	-3.30	5.45
BE	-0.81	8.54	-3.53	0.79	1.01	7.47	3.07	4.92	7.33	-0.76	-3.48	3.34
DE	0.79	2.51	0.41	32.03	1.01	7.51	3.13	5.10	7.55	-0.66	-3.67	3.74
DK	0.39	7.27	-7.52	19.93	0.01	-15.29	26.63	5.77	-6.88	-0.45	-2.91	2.71
ES	-3.12	8.72	-3.40	0.83	1.01	7.51	3.13	5.10	7.55	-0.66	-3.67	2.01
FI	-0.40	10.04	-5.82	5.88	-3.14	4.53	0.37	3.65	6.48	-1.32	-2.30	2.80
FR	0.79	8.72	-3.40	0.83	1.01	7.51	3.13	5.10	7.55	-0.66	-3.67	3.74
GR	20.90	9.67	-8.20	4.39	-6.58	1.47	63.43	5.51	7.82	-0.43	-30.38	4.16
IE	-0.29	6.52	-3.89	-1.41	-2.37	0.31	9.16	17.21	8.37	-0.46	-19.03	2.60
IT	0.77	8.72	-3.40	0.83	1.01	7.51	3.13	5.10	7.55	-0.66	-3.67	4.69
LU												
NL	31.83	21.40	-3.40	0.83	1.01	7.51	3.13	5.10	7.55	-0.66	-3.67	5.24
PT	0.31	7.96	-7.01	19.76	0.36	-16.47	32.17	5.60	7.95	-0.44	-3.08	4.17
SE	-1.01	10.19	-4.49	0.77	0.96	9.93	2.70	2.11	10.35	-0.58	-3.92	3.47
UK	0.75	8.72	-3.40	0.83	1.01	7.51	3.13	5.10	7.55	-0.66	-3.67	3.74
US	0.79	2.51	0.41	-4.59	-4.25	-1.38	0.56	5.08	4.85	0.27	2.94	0.53

(Period averages are geometric means of yearly changes. Sources: author's calculations from UNFCC, Eurostat, Statec data.)

Table 7: Cumulative changes in eco-environmental performance 1995-2009

Country		efficiency	tech. change	Malmquist
	1995	2009	2009	2009
AT	100	80.77	210.17	169.76
BE	100	91.42	158.38	144.79
DE	100	94.02	167.14	157.15
DK	100	90.54	145.40	131.65
ES	100	60.52	132.08	79.94
FI	100	106.63	147.30	157.06
FR	100	82.11	167.14	137.24
GR	100	62.32	176.98	110.29
IE	100	120.21	143.20	172.13
IT	100	64.42	189.89	122.33
LU	100	100		
NL	100	73.07	204.48	149.42
PT	100	67.69	177.20	119.95
SE	100	100	161.23	161.23
UK	100	89.40	167.15	149.44
US	100	114.31	107.68	123.08

(Sources: author's calculations from UNFCC, Eurostat, Statec data.)

4.1 Is there an efficiency kuznet curve?

The comparison of environmental efficiency scores to pure economic efficiency scores (figure 6) evidences the relevance of the environmental constraint. (Economics efficiency scores are obtained by evaluating the ability of countries to expand production given inputs, regardless of pollutants. Results are given in Table 11 in the appendix.) Indeed, one can see that more countries make a fully efficient use of inputs, and that average period scores are higher (0.88 versus 0.66), when considering pure economic performances. The scatterplot of EPIs (for year 2009) versus pure economic efficiency does not evidence any clear relation between the two scores. Sweden and Luxembourg are both economic and environmentally efficient, while a group of countries with bad environmental performances have high economic efficiency (UK, US and Ireland). Simple regression lines, obtained from the non-parametric regression of environmental performance on productive efficiency scores, are superimposed to the scatterplot to check for the existence of a DEA-based environmental Kuznet curve (EKC).[14] The curves' shape evidence inverted U for some years and monotonic relations for others. Clearly, a monotonic relation in this context implies that higher levels of economic efficiencies lead to higher level of environmental efficiencies. An inverted U suggests instead a trade-off, by which, at lower levels of economic efficiency, efficiency gains lead to environmental improvements, whereas at high level of economic efficiency efficiency gains lead to proportional increase in environmental degradation. The inspection of the curves also reveal that the relation between economic and environmental performances is not stable over time. Over the period, the curve becomes lower, meaning that same levels of pure economic efficiency are associated with lower levels of environmental efficiency.

The comparison of Malmquist indices of environmental performance to indices of pure economic performance also finds no clear and stable pattern in the data.

[14] Regression curves are obtained with local polynomial fitting, which fits regression lines over portions of data selected by a parameter called the bandwidth.

In conclusion, an EKC does not seem a stable feature of this data.

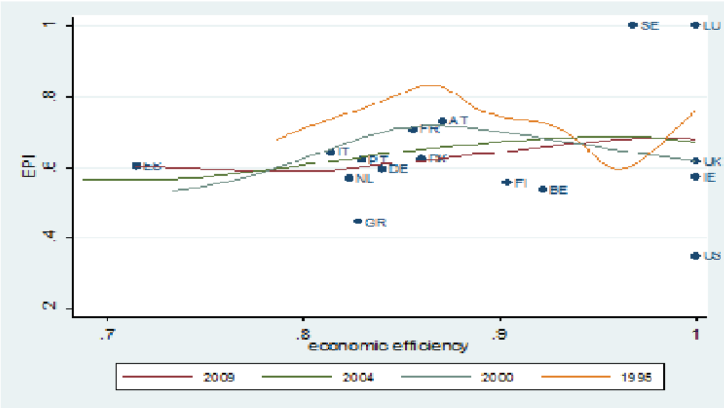

Figure 6: Kuznet curves, 1995-2009.(Source: UNFCC, Eurostat).

4.2 The decomposition of carbon intensity

The EPI index can be interpreted as an enhanced measure of carbon intensity (Zhou et al., 2008). Indeed, these two measures are significantly positively correlated, as noted in previous sections. This section presents a decomposition of carbon intensity changes over time using distance functions. This provides a link between environmental performance, economic efficiency and technical progress. It shows that the change in carbon intensity can be decomposed into the contribution of changes in labour productivity scaled by changes in production and labour input. Labour productivity, in turn, is decomposed in the contribution of capital accumulation, efficiency gains and technical progress (Kumar and Russell, 2002).

The change over time of carbon intensity can be written as the product of changes in the reciprocal of labour productivity and emissions per capita:

$$\begin{aligned}\frac{CO2_{t+1}/Y_{t+1}}{CO2_t/Y_t} &= \frac{Y_t}{Y_{t+1}}\frac{L_t}{L_{t+1}}\frac{L_{t+1}}{L_t}\frac{CO2_{t+1}}{CO2_t} \\ &= \left(\frac{Y_{t+1}/L_{t+1}}{Y_t/L_t}\right)^{-1}\frac{CO2_{t+1}/L_{t+1}}{CO2_t/L_t}\end{aligned} \tag{8}$$

(This is done by multiplying and dividing carbon intensity by the change in labour input.) Here, CO2 denotes carbon dioxide emissions, Y production, and K and L, respectively, capital stock and labour inputs.

Following Kumar and Russell (2002), we decompose the first term, labour productivity, into the product of changes in efficiency, changes in technology, and (a function of) changes in capital accumulation:

$$\frac{CO2_{t+1}/Y_{t+1}}{CO2_t/Y_t} = \left(TECH \times EFF \times f(\frac{K_{t+1}/L_{t+1}}{K_t/L_t})\right)^{-1} \frac{CO2_{t+1}/L_{t+1}}{CO2_t/L_t} \tag{9}$$

where TECH denotes technical progress, EFF changes in productive efficiency, and f is a function of change in capital intensity.[15] One can see that the product of the first two terms in the equation above represent a Malmquist index of production obtained under a CRS technology. Assuming that emissions are an increasing function of production, the change in CO2 per capita can be expressed as the product of the decrease in labour input and an *increasing* function of the change in production:[16]

$$\frac{CO2_{t+1}/L_{t+1}}{CO2_t/L_t} = (L_{t+1}/L_t)^{-1} g(Y_{t+1}/Y_t), \qquad g'(\cdot) > 0, \quad g''(\cdot) > 0 \tag{10}$$

Thus, the equation 9 for carbon intensity becomes:

$$\frac{CO2_{t+1}/Y_{t+1}}{CO2_t/Y_t} = \left(TECH \times EFF \times f(\frac{K_{t+1}/L_{t+1}}{K_t/L_t})\right)^{-1} (L_{t+1}/L_t)^{-1} g(Y_{t+1}/Y_t) \tag{11}$$

Thus, carbon intensity is increasing in production, and decreasing in efficiency gains, technical progress, capital accumulation and labour. *Viceversa*, carbon efficiency is an increasing function of technical progress, efficiency gains, capital accumulation, employment growth, and a decreasing function of production growth. It is easy to see that technical progress incorporating newer technologies and new capital, likely to be more energy efficient, can lead to improvements in environmental efficiency. The last term is more difficult to interpret. If we assume that output grows at a constant rate α, and that the technology that transforms output in emissions changes over time, we can write the last term as follows:

$$g(Y_{t+1}/Y_t) = g_1(Y_{t+1})/g_2(Y_t), \qquad Y_{t+1}/Y_t = \alpha \tag{12}$$

Rearranging and taking derivatives we get

$$g_1^{'}(Y_t)\alpha = g(\alpha) g_2^{'}(Y_t), \tag{13}$$

Then,

$$g(\alpha) = \alpha \frac{g_1^{'}(Y_t)}{g_2^{'}(Y_t)} \tag{14}$$

The expression above offers an interpretation for the last term of equation 11. One can see that the function g can be written as the ratio of two slopes evaluated at the same point Y_t. Thus, this function represents changes in the way that output is transformed into emissions over time. (The derivative of $g1$ wth respect to Y tells us how much $CO2$ emissions increase following a unit change in output.) It is generally agreed that increases in output lead to increases in pollution through increased energy consumption. One should note, however, that

[15] Under CRS and assuming that production is described by a standard Cobb-Douglas function in K and L, it is possible to show that $f(K/L) = (\frac{K_{t+1}/L_{t+1}}{K_t/L_t})^{\alpha}$.

[16] g is a positive and increasing function of production. Its second negative with respect to production is also positive, so that emissions are increasing at increasing rates in output. Furthermore, when production is zero we assume that emissions are zero, so that $g(0) = 0$.

the same level of output can generate different level of emissions depending on the combination of inputs used (the technology adopted). For example, regardless of energy, if a technology uses a bundle of inputs that generates less pollution than other bundles, this should lead to increases in environmental efficiency. (Notice that the decomposition is written in terms of CO2, but is valid also when considering total emissions or any other pollutant in this article.)

The equation 11 above can be written in terms of distance function as follows:

$$\frac{CO2_{t+1}/Y_{t+1}}{CO2_t/Y_t} = \underbrace{\frac{D^{t+1}(k^{t+1}, y^{t+1})}{D^t(k^t, y^t)}}_{efficiency\ gains} \times \underbrace{\left[\left(\frac{D^t(k^{t+1}, y^{t+1})}{D^{t+1}(k^{t+1}, y^{t+1})}\right)\left(\frac{D^t(k^t, y^t)}{D^{t+1}(k^t, y^t)}\right)\right]^{\frac{1}{2}}}_{technical\ progress} \times$$
$$\underbrace{\left[\left(\frac{D^t(k^t, y^t)}{D^t(k^t, y^t)}\right)\left(\frac{D^{t+1}(k^t, y^t)}{D^{t+1}(k^{t+1}, y^{t+1})}\right)\right]^{\frac{1}{2}}}_{capital\ deepening} \times$$
$$z(D^{t+1}_{env}(x_{t+1}, CO2_{t+1})/D^t_{env}(x_t, CO2_t)) \qquad (15)$$

The first three terms, which represents the Kumar and Russell decomposition, are written in terms of standard output distance function, where one output (Y/L=y) is expanded for a given level of the single input (K/L=k). The latter term is left unspecified at this stage. We simply note that it should represent the change in environmental performance for a DEA technology where the objective is to contract the emissions for a certain level of input use. This is interesting because it highlights that the impact of production on CO2 is determined by inputs' use rather than output itself. (This is also supported by previous study, such as the one of Fare et al., 2004, .)

Table 8 presents figures for carbon intensity and each of its component for the 16 countries from 1995 to 2009. (Data in the table refer to total greenhouse gases emissions.) One can see that, while capital accumulation is sustained and employment grows at positive rates, efficiency gains and technical progress figures are poor. Many countries experience efficiency losses and nearly all of them technical regress.[17] (Recall that these terms enter with a minus in the equation for carbon intensity.) Thus, these data suggest that reductions in carbon intensity have been largely driven by improvements in labour productivity, sustained primarily by capital accumulation. This also implies that, had productivity growth being higher, due to efficiency improvements and postive technical progress, the countries performance could have improved even further.[18]

In summary, the decomposition above establishes a link between technical progress, economic efficiency and environmental efficiency. More research should lead to the complete specification of the decomposition in this section using environmental DEA technologies.

[17] For a discussion of these results one can see Peroni (2012).

[18] One should note that figures in the table are period averages, so the decomposition cannot hold exactly. Furthermore, the form of the production component is unknown.

Table 8: Decomposition of carbon intensity

Country	Δ carbon int.	EFF	TECH	$f(\Delta K/L)$	ΔL	$g(\Delta Y)$
AT	-1.90	0.26	0.35	0.40	0.93	0.12
BE	-2.67	-0.16	0.31	0.24	0.99	-1.22
DE	-3.18	0.52	-0.23	1.05	0.47	-1.29
DK	-2.43	0.07	-1.27	1.54	0.63	-1.36
ES	-0.96	-1.13	-0.14	0.81	2.50	1.13
FI	-3.00	0.69	-0.17	0.77	1.30	-0.27
FR	-2.24	0.08	0.21	0.51	0.90	-0.44
GR	-0.02	0.27	-1.65	1.20	1.00	0.92
IE	-3.07	-0.21	-1.54	2.44	2.95	0.71
IT	-0.53	-1.46	-0.43	0.91	0.92	-0.51
LU	-2.33	0.00	-0.15	0.04	3.57	1.27
NL	-2.78	0.01	0.08	0.52	1.38	-0.66
PT	-0.69	-1.89	-2.64	4.95	0.73	0.53
SE	-3.28	1.34	-1.04	0.96	0.57	-1.31
UK	-2.84	0.37	-2.19	2.27	0.83	-1.51
US	-1.47	0.02	-0.01	0.76	0.78	0.13

Legend: Data are average yearly changes (geometric means). (Sources: UNFCC, Eurostat.)

5 Conclusions

This study investigated the relation between environmental and economic performance for a group of EU member states and the US from 1995 to 2009 using recently published data from the UN Framework Convention on Climate Change. Rather than resorting to standard Environmental Kuznet Curves (EKC), the article models environmental performances using an environmental DEA technology. This regards greenhouse gas emissions as an undesirable output of a productive process, and assumes costly disposability of pollutants. Using this approach, the study computes an environmental performance index (EPI) which allow us to grade countries according to their ability to increase output and decrease emissions at a given level of inputs.

Standard indicators of environmental performances, such as greenhouse gas emissions per capita and carbon intensity, exhibit a substantial decline over the period analysed for nearly all countries, which contrasts with a general perception of improvements in environmental quality in Western countries. The descriptive analysis of the data shows that a non-standard inverse U shaped curve links GDP per capita growth and emissions per capita growth. We find several interesting results:

- Two countries are fully efficient with respect to the EU-US environmental efficiency frontier: Luxembourg and Sweden. Worst performers are US, Greece and Finland. Efficient countries obtain the maximum possible output with the minimum amount of emissions. The simultaneous increase production and decrease emissions can only be achieved through technical progress. In contrast, countries below the frontier can expand their output while reducing pollution.

- The comparison of EPIs to pure economic efficiency indices highlights the relevance of the environmental constraint. The productive efficiency scores are substantially lowered when greenhouse emissions are taken into account. Furthermore, there is no evidence of a DEA-based EKC in the data.

- Malmquist indices, better suited to describe the time series evolution of efficiency scores than EPIs, evidence a general improvement in environmental performances over the period. Countries which improved the most were Sweden, Germany, Finland and the Netherlands. These improvements were driven by technical progress. Many countries, however, experienced efficiency losses which determined a poorer environmental performance. Furthermore, the net effect of recessions on environmental performance is negative due to negative technical progress, possibly due to a decline in the rate of adoption of cleaner productive processes.

- A decomposition of carbon intensity using standard output distance functions establishes a positive link between technical progress, economic efficiency gains and carbon intensity. This may explain the findings regarding the EKCs.

The analysis of this article has several limitations. This productive efficiency analysis does not consider allocative efficiency issues nor can capture the "displacing" of emissions to lesser-developed countries. The computation of Malmquist indices under VRS poses problems of feasibility not solvable with standard method available in the literature. This involves a country positioned on the frontier. Moreover, our sample is limited to Western countries, data from developing countries are not considered. The rigorous decomposition of carbon intensity using environmental DEA technology and distance functions requires also further research. The study presented here, however, opens the possibility of a growth accounting exercise that takes into account environmental issues.

References

Ang, B. (1999). Is the energy intensity a less useful indicator than the carbon factor in the study of climate change? *Energy Policy*, 27:943–946.

Caves, D., Christensen, L., and Diewert, W. (1982). The economic theory of index numbers and the measurement of input, output, and productivity. *Econometrica*, 50:73–86.

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

Chen, P. and Yu, M. (2012). Total factor productivity growth and directions of technical change bias: evidence from 99 oecd and non-oecd countries. Annals of Operations Research, Online First.

Corrado, C., Hulten, C., and Sichel, D. (2009). Intangible capital and u.s. economic growth. *Review of Income & Wealth*, 55:661–685.

DiMaria, C. and Ciccone, J. (2008). Luxklems: Productivite et competitivite. Perpectives de Politique Economique, N 8, Le Gouvernment du Grand-Duche de Luxembourg.

Fare, R. and Grosskopf, S. (2004). Modelling undesirable factors in efficiency valuation: a comment. *European Journal of Operational Research*, 157:242–245.

Fare, R., Grosskopf, S., Lovell, C., and Pasurka, C. (1989). Multilateral productivity comparison when some outputs are undesirable. *The Review of Economics and Statistics*, 71:90–98.

Fare, R., Grosskopf, S., and Lovell, C. K. (1994a). *Production Frontiers*. Cambridge University Press.

Fare, R., Grosskopf, S., Norris, M., and Zhongyang, Z. (1994b). Productivity growth, technical progress and efficiency change in industrialised countries. *American Economic Review*, 84:666–83.

Fare, R., Grosskopf, S., and Sancho, F. H. (2004). Environmental performance: an index number approach. *Resource and Energy economics*, 26:343–352.

Farrell, M. (1957). The measurement of productive efficiency. *Journal of the Royal Statistical Society, Series A*, 120:253–90.

Hua, Z., Bian, Y., and Liang, L. (2007). Eco-efficiency analysis of paper mills along the huai river: An extended DEA approach. *Omega*, 35:578 – 587.

Kumar, S. and Russell, R. (2002). Technological change, technological catch-up, and capital deepening: relative contributions to growth and convergence. *The American Economic Review*, 92:527–48.

Peroni, C. (2012). Productivity and competitiveness in luxemnbourg; productivity & the crisis. Perpectives de Politique Economique, N 18, Ministre de l'economie e du commerce exterieur du Grand-Duch de Luxembourg.

Ravishankara, A., Daniel, J., and Portmann, R. (2009). Nitrous oxide (n2o): The dominant ozone-depleting substance emitted in the 21st century. *Science*, 326:123–125.

Tyteca, D. (1996). On the measurement of the environmental performance of firms. *Journal of environmental management*, 46:281–308.

Tyteca, D. (1997). Linear programming models for the measurement of environmental performance of firms — concepts and empirical results. *Journal of Productivity Analysis*, 8:183–197.

Zaim, O. and Taskin, F. (2000a). Environmental efficiency in carbon dioxide emissions in the oecd: a non-parametric approach. *Journal of Environmental Management*, 58:95–107.

Zaim, O. and Taskin, F. (2000b). A kuznets curve in environmental efficiency: an application to OECD countries. *Journal of Environmental and Resource Economics*, 17:21–36.

Zhou, P., Ang, B., and Poh, K. (2006). Slacks-based efficiency measures for modeling environmental performance. *Ecological Economics*, 60:111 – 118.

Zhou, P., Ang, B., and Poh, K. (2008). Measuring environmental performance under different environmental technologies. *Energy Economics*, 30:1–14.

Zhou, P., Ang, B., and Poh, K. (2010). Total factor carbon emission performance: a Malmquist index analysis. *Energy Economics*, 32:194–201.

6 Appendix: tables

Table 9: Summary Statistics: means

Country	GDP	K	L	CO2	N2O	GHG	GDP pc	K pc	GHG pc	CO2 pc	N2O pc	GHG/ GDP	nrg	nrg/ GDP
AT	211.13	477.38	37.81	71.11	5.98	85.23	55.71	125.65	22.56	18.81	1.59	0.41	25.28	0.12
BE	254.22	536.58	41.52	122.99	10.06	142.98	61.16	128.87	34.58	29.72	2.44	0.57	36.53	0.14
DE	1996.62	4234.50	389.98	885.64	68.48	1036.95	51.13	108.29	26.63	22.74	1.76	0.53	224.00	0.11
DK	137.39	264.71	27.71	58.50	7.31	72.42	49.55	95.22	26.21	21.18	2.65	0.53	15.18	0.11
ES	801.52	1909.25	172.61	310.28	29.27	380.21	46.62	109.33	22.14	18.02	1.73	0.47	83.51	0.10
EU15	8956.04	0.00	1698.64	3369.63	329.71	4127.15	52.62		24.38	19.88	1.96	0.47	975.38	0.11
FI	123.74	254.15	23.14	61.93	6.53	74.20	53.22	109.33	32.18	26.85	2.83	0.61	24.84	0.20
FR	1387.95	2860.13	254.52	409.20	76.01	565.68	54.41	111.81	22.29	16.11	3.01	0.41	155.78	0.11
GR	194.69	394.26	44.13	103.57	8.29	125.20	44.08	88.91	28.39	23.46	1.89	0.64	19.35	0.10
IE	104.82	167.77	17.49	43.60	8.40	65.94	59.85	94.12	38.38	25.19	4.99	0.64	10.96	0.10
IT	1286.99	2448.47	235.78	464.15	36.48	547.66	54.69	103.38	23.27	19.72	1.56	0.43	125.19	0.10
LU	21.79	73.25	2.82	10.03	0.48	11.02	76.97	258.87	39.35	35.78	1.73	0.51	3.78	0.18
NL	417.28	901.65	81.04	173.99	16.23	214.66	51.38	110.73	26.64	21.54	2.03	0.52	50.67	0.12
PT	162.98	306.76	49.80	60.63	5.39	78.76	32.70	61.15	15.80	12.16	1.09	0.48	17.40	0.11
SE	226.05	405.65	43.13	54.82	7.60	69.66	52.28	93.79	16.20	12.75	1.77	0.31	34.11	0.15
UK	1400.67	2158.00	278.40	547.35	43.73	666.38	50.22	77.18	24.03	19.71	1.58	0.48	148.80	0.11
US	8974.29	15135.45	1390.49	5838.01	320.48	6945.69	64.41	108.30	50.00	42.02	2.31	0.78	2449.83	0.27
Sample	1870.35	2033.00	341.81	740.32	57.67	894.69	53.46	111.56	27.82	22.68	2.17	0.49	288.03	0.13

Legend: nrg denotes energy consumption. Units: Greenhouse gases emissions are in billion tonnes of CO2 equivalent (1000 gigagrams - Gg); energy consumption is recorded in million tonnes of oil equivalent (TOE); GDP and capital stock data are in billion euros and employment in 100.000 units. pc indicates that data are in per capita terms.

Table 10: Eco-environmental performances (EPI) 1995-2009

Country	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
AT	0.91	0.91	0.86	0.88	0.84	0.82	0.79	0.79	0.75	0.73	0.69	0.70	0.69	0.69	0.73
BE	0.59	0.59	0.60	0.56	0.55	0.54	0.56	0.58	0.56	0.52	0.52	0.52	0.52	0.50	0.54
DE	0.61	0.62	0.60	0.61	0.59	0.57	0.58	0.60	0.60	0.59	0.60	0.59	0.58	0.58	0.60
DK	0.68	0.61	0.64	0.66	0.64	0.66	0.66	0.68	0.62	0.66	0.68	0.60	0.60	0.62	0.62
ES	0.84	0.89	0.80	0.79	0.68	0.63	0.66	0.65	0.63	0.57	0.55	0.56	0.53	0.56	0.61
FI	0.57	0.55	0.55	0.57	0.55	0.56	0.53	0.53	0.48	0.51	0.60	0.51	0.51	0.56	0.56
FR	0.82	0.83	0.80	0.79	0.76	0.75	0.79	0.81	0.77	0.73	0.72	0.72	0.70	0.68	0.71
GR	0.72	0.68	0.60	0.53	0.49	0.46	0.49	0.51	0.50	0.48	0.45	0.46	0.42	0.44	0.45
IE	0.60	0.64	0.61	0.56	0.52	0.51	0.51	0.55	0.56	0.57	0.56	0.56	0.56	0.53	0.58
IT	0.95	0.97	0.89	0.87	0.78	0.73	0.76	0.72	0.69	0.63	0.61	0.61	0.60	0.60	0.64
LU	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
NL	0.61	0.63	0.62	0.63	0.63	0.61	0.62	0.62	0.59	0.57	0.58	0.58	0.57	0.57	0.57
PT	0.91	0.97	0.86	0.78	0.66	0.65	0.66	0.63	0.65	0.60	0.60	0.61	0.59	0.59	0.62
SE	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
UK	0.66	0.67	0.67	0.67	0.65	0.63	0.67	0.69	0.68	0.66	0.65	0.63	0.59	0.59	0.62
US	0.45	0.46	0.44	0.45	0.42	0.39	0.41	0.41	0.41	0.39	0.38	0.37	0.34	0.34	0.35

Table 11: Economic performances 1995-2009

Country	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
AT	0.84	0.84	0.84	0.84	0.83	0.85	0.83	0.85	0.85	0.85	0.84	0.88	0.88	0.89	0.87
BE	0.97	0.96	0.97	0.93	0.92	0.95	0.94	0.96	0.94	0.92	0.91	0.93	0.93	0.93	0.92
DE	0.81	0.80	0.78	0.78	0.77	0.77	0.78	0.78	0.78	0.78	0.80	0.85	0.86	0.88	0.84
DK	0.84	0.83	0.82	0.82	0.82	0.83	0.83	0.82	0.82	0.83	0.84	0.85	0.84	0.86	0.86
ES	0.84	0.82	0.80	0.78	0.74	0.73	0.73	0.72	0.71	0.69	0.68	0.68	0.68	0.69	0.71
FI	0.79	0.78	0.79	0.81	0.81	0.83	0.83	0.83	0.83	0.87	0.88	0.91	0.93	0.95	0.90
FR	0.85	0.84	0.85	0.84	0.83	0.84	0.86	0.85	0.82	0.82	0.83	0.85	0.86	0.86	0.86
GR	0.80	0.78	0.77	0.76	0.76	0.76	0.78	0.78	0.79	0.78	0.78	0.79	0.79	0.81	0.83
IE	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
IT	1.00	0.96	0.94	0.93	0.90	0.89	0.90	0.87	0.85	0.83	0.82	0.83	0.83	0.83	0.81
LU	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
NL	0.82	0.82	0.81	0.80	0.79	0.80	0.79	0.78	0.76	0.77	0.79	0.81	0.83	0.84	0.82
PT	1	1	0.97	0.93	0.89	0.85	0.82	0.79	0.76	0.75	0.75	0.76	0.77	0.80	0.83
SE	0.80	0.80	0.80	0.82	0.85	0.87	0.87	0.88	0.90	0.94	0.95	0.97	0.98	0.98	0.97
UK	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
US	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Legend: Economic performance scores computed under VRS.

Table 12: Environmental performances: Malmquist indices 1995-2009

Country	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
AT	12.58	4.22	5.59	0.85	-3.36	4.86	1.50	-5.34	4.54	38.61	-10.66	5.24	-0.86	3.31
BE	-0.25	10.48	-3.33	9.58	6.75	0.22	4.31	-3.01	0.38	2.94	5.22	5.57	-3.72	3.71
DE	1.31	5.99	4.41	7.82	4.19	-0.22	3.05	2.14	4.29	5.21	4.03	6.05	-1.27	-0.59
DK	-11.12	17.39	8.79	8.12	14.02	-4.38	5.11	-9.61	13.15	5.24	-7.91	-6.02	2.26	-1.75
ES	-3.12	-7.15	-9.18	-14.93	1.30	1.25	-1.20	-2.00	-1.62	-1.64	7.02	1.50	5.55	4.38
FI	-3.78	9.20	9.25	6.98	11.88	-8.54	0.67	-7.92	13.40	19.84	-13.66	6.21	7.84	0.31
FR	-0.30	5.25	1.38	7.68	7.07	2.13	2.99	-3.69	1.99	2.05	4.71	4.54	-2.84	-0.23
GR	-11.41	-4.91	-8.92	3.34	5.81	5.14	14.80	-7.65	14.94	-5.41	6.71	-1.31	3.34	-0.31
IE	6.35	4.74	-0.73	2.83	2.37	-3.14	7.48	2.59	4.82	1.03	15.43	8.44	-5.87	10.97
IT	0.77	6.35	7.43	0.18	2.51	0.41	-4.59	-4.25	-1.38	0.56	5.08	4.85	0.27	2.94
LU														
NL	6.00	21.80	4.73	5.65	-5.12	-1.95	0.50	-3.54	3.40	5.14	5.69	5.66	-0.83	-3.66
PT	5.75	-0.91	-4.22	-4.08	7.37	0.25	-4.56	4.96	-3.15	4.17	8.04	4.80	-0.74	1.90
SE	-1.01	9.27	2.56	11.70	10.19	-4.49	0.77	0.96	9.93	2.70	2.11	10.35	-0.58	-3.92
UK	0.83	8.82	2.42	8.28	6.61	1.78	4.83	-0.68	4.44	1.15	2.35	0.89	-1.30	0.97
US	1.60	4.11	3.62	5.21	1.48	1.06	0.96	1.34	1.52	1.58	0.73	-0.01	-2.00	-0.05