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Assessing country heterogeneity

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Abstract

A large body of literature explores convergence in environmental performance (*EP*) using a simple measure of the percentage change of per capita CO_2 as dependent variable and the level of per capita CO_2 and GDP as explanatory variables. As such it conforms to the standard convergence literature in the economic growth literature. This study differs from these studies by constructing a measure based on production theory, where production processes explicitly results in the production of two outputs; a good output (GDP) and a bad output (CO_2). Based on this we derive an *EP* index that can be expressed as the ratio of the inverse of the change of the emission intensity. We use the derived *EP* index to test the β-convergence hypothesis for a panel of 94 countries. The results reveal strong evidence in support of β-convergence in environmental, or carbon, performance. Moreover we find evidence of heterogeneity between groups of countries in line with the concept of "club" convergence and also heterogeneity between countries within country groups, especially for the high-income group. Additionally, we find evidence of a negative relation between environmental performance and fossil fuel share both at the global level as well as within sub-samples, which tend to vary with capital intensity. As such the results conform to the results from studies of the dynamics of per capita emissions. These results are therefore very informative and can help in both regional and international negotiations regarding burden sharing of global CO_2 emissions. The results also suggest a balanced policy mix between efficiency and conservation policies in order to promote good environmental performance.

Keywords: Convergence, Environmental Performance, Fossil fuel, Kyoto Protocol, Spillovers

JEL Classification:

1. Introduction

The impact of economic activity on the environment is attracting increasing attention from policy makers, firms and the academia. This is partly due to the increasing evidence of the negative impact that human activity have on the environment. Furthermore, there has been an increasing interest concerning the dynamic properties of emissions; how they change over time as a result of changes in income, income distribution, technical development, etc. As a result of the latter a number of studies have been carried out to analyze the relationship between economic growth and changes of emission based on the Environmental Kuznets Curve hypothesis (EKC). The EKC hypothesis states that environmental degradation follows an inverted U-shaped relationship as a country's GDP grows over time (Grossman and Krueger, 1991, 1995). Comprehensive reviews of the EKC literature can be found in Levinson (2002), Dinda (2004), Stern (2004), Lieb (2004) and Kijima et al. (2010).

A recent strand in the literature is related to finding an appropriate measure for environmental performance (*EP*), as an assessment tool for economic and environmental policy, and to assess if *EP* converges across countries and over time for a given country. Whether there is convergence or not in *EP* across countries has implications for future global emissions negotiations, such as the Kyoto protocol in terms of quota allocations and also on regional level negotiations. Therefore having an appropriate measure of *EP* and consequently providing evidence for convergence/divergence is extremely important. The majority of the studies in this strand of the literature measure *EP* using CO_2 emissions as a ratio of population, GDP or energy consumption. Recent papers in this line of research includes; Strazicich and List (2003), Ngugen (2005), Aldy (2006, 2007), Ezcerra (2007), Panopoulou and Pantelidis (2007) Camarero et al. (2008), Westerlund and Basher (2008), Brock and Taylor (2010), Camarero et al. (2012), and Brännlund et.al (2014a). These studies implemented various econometric methods from both parametric to non-parametric approaches to address the question of convergence in environmental performance measured simply as per capita CO_2 emissions, as a ratio of GDP or energy consumption. However, according to Ramanathan (2002) these studies only provide a partial picture of environmental performance as they only consider emissions originating from economic activities.

There are other existing approaches in measuring environmental performance, as an alternative to these measures. These other approaches in measuring *EP* are diverse but can be grouped into three main perspectives, (1) the product cycle analysis/assessment, (2) the environmental accounting perspective, and (3) the production theory framework. Each of these approaches focus on different aspects of *EP*, albeit with different strengths and weaknesses, which are well documented in Tyteca (1996) and Olsthoorn et al. (2001).

Our focus in this paper is to propose to use a simple but relevant theory for measuring *EP*, that is based on production theory, inspired by recent work that includes Färe et al. (2006), Zaim and Taskin (2000), Zofio and Prieto (2001), Zaim (2004), Zhou et al.(2006) and Picazo-Tadeo and García-Reche (2007). Therefore our paper makes three key contributions to the literature.

Firstly, we propose to use a simple theory in measuring *EP* that explicitly considers that the production process simultaneously results in both good and bad outputs. This framework is based on Färe et al. (2006). Secondly, based on this, we calculate, in a first step, an *EP* index for each country for a sample of 94 countries for the period (1971 to 2008). In a second step we use the *EP* index in a regression analysis in order to test for β-convergence in environmental performance. As far as we know we are among the first to do this based on a production theory framework. The only paper in the literature that studied convergence based on the production theory framework is Camarero et al. (2008) and Brännlund et al. (2014), but unlike our paper, Camarero et al. focus only on a sample of OECD countries, while Brännlund et al. focus on Swedish industries. Hence our work can therefore be seen as an extension of Camarero et al. (2008) on two fronts; it extends to a global sample, and it looks specifically at it from a β-convergence perspective as done in Brännlund et al. (2014) for Swedish industries.

Thirdly, we also consider heterogeneity in the rate of convergence both between groups of countries, in line with "club" convergence, and also between countries. This is important for both regional and international negotiations regarding burden sharing in global environmental emissions, especially CO_2 emissions. It is important to know the contributions to growth in CO_2 emissions by regions and by countries to aid the negotiations in burden sharing of global CO_2 emissions. We also use econometric techniques that accommodate both country and time specific effects that help to reduce spillover effects (cross-sectional dependence) from common shocks, and therefore reduce the possible bias that spillover effects can generate on the estimated parameters and also reduces possible cofounding effects.

The rest of the paper is organized as follows. Section two provides the theory and method for measuring the *EP* index, and section three provides details on the empirical approach for the study. The data is presented in section four, and the results are presented in section five.

Section six, finally, contains some concluding comments and policy implications from the study.

2. Theory and method

The theoretical approach outlined here follows primarily Färe et al. (2006). The theory as such is thus not novel, and the theoretical presentation here is motivated mainly to lay the foundation to the performance index that will be used subsequently in the empirical analysis.[1]

In particular the environmental performance index, *EP*, that will be used here is based on neoclassical production theory, which explicitly recognize that the production process results in both good and bad outputs. More specifically, this means that we will use a quantity approach based on ratios of output distance functions. In this particular case, with one good (GDP) and one bad (CO_2) output it turns out that this ratio of distance functions results in a simple expression showing the growth path of the inverse of the emission intensity.

The distance functions are here defined on the output possibility set, $P(x)$, expressed as $P(x)=\{(y,b): x \text{ can produce} (y,b)\}$. Here y is good output, b is bad output, and x a vector of inputs. In general y and b are vectors. $P(x)$ is assumed to be convex, closed, and bounded, i.e., compact, with inputs and good outputs being freely disposable. Good outputs being freely disposable is formally expressed as $(y,b)\in P(x) \text{ and } y' \leq y \text{ then } (y',b)\in P(x)$, which means that a good output can always be reduced without reducing any other output.

In addition to these technological properties, shaping the frontier of $P(x)$, additional properties must be introduced to distinguish good outputs from bad outputs. Firstly, good and bad outputs are assumed to be weakly disposable. This means that good and bad outputs can always be simultaneously reduced proportionally. Since bad outputs are weakly disposable, a reduction in a bad output, or emissions, cannot be accomplished without giving up some good output directly or indirectly (Färe et al., 2006, p. 261).

A second technological property, imposed to distinguish good outputs from bad outputs, is that (y, b) is null-joint, i.e. good output cannot be produced without producing any bad output.In order to form a good output quantity index, Shephard output distance functions are defined for

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[1] See also Brännlund & Lundgren (2014), and Brännlund et.al. (2014), for applications on Swedish industry data.

the good output sub-vector between time periods t and $t+1$ as follows (Färe et al., 2006, p. 261):[2]

$$\begin{aligned} D_y^t\left(x^o, y^t, b^o\right) &= \min\left\{\theta : \left(\frac{y^t}{\theta}, b^o\right) \in P^t\left(x^o\right)\right\} \\ D_y^t\left(x^o, y^{t+1}, b^o\right) &= \min\left\{\theta : \left(\frac{y^{t+1}}{\theta}, b^o\right) \in P^t\left(x^o\right)\right\} \end{aligned}, \tag{1}$$

of which the solutions, θ^*, gives the maximum feasible proportional expansion of good outputs, given inputs, bad outputs and technology. As such $D_y^t(\cdot) = \theta^*$ reflects technical efficiency in production by measuring the distance between the actual good output production level and the best practice good output production level. By the definitions in equation (3), the good output sub-vector distance function is homogeneous of degree +1 in good output, y.

Then, by letting x^{o} and b^{o} be given reference levels of inputs and bad outputs, respectively, a good output quantity index is specified for the output vectors y^t and y^{t+1} as follows:

$$Q_y^t\left(x^o, b^o, y^{t+1}, y^t\right) = \frac{D_y^t\left(x^o, y^{t+1}, b^o\right)}{D_y^t\left(x^o, y^t, b^o\right)}, \tag{2}$$

which reflects the change in good output production from period t to period $t+1$, holding everything else constant. Specifically, if $y^{t+1} > y^t$ then $Q_y^t > 1$, as the distance function is increasing in y. In the general case, including multiple good and bad outputs, all these conditions and the quantity index in equation (2) depend on the reference vector, (x^o, b^o) (Färe and Grosskopf, 2003, p. 57). In the special case of a single good and single bad output technology, as in this application, the quantity index is independent from (x^o, b^o) and as a consequence the estimation is simplified significantly.

The quantity index being independent of (x^o, b^o) in the single good and bad output case follows from the distance function being homogenous of degree +1 in good outputs, y. Given this we can, in the single good and bad output case, express the good output quantity index in equation (2) as:

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[2] Regarding the Shephard output distance function, Färe et al. (2006) refer to Shephard, R.W. (1970) Theory of Cost and Production Functions. Princeton University Press, Princeton.

$$Q_y^t\left(y^{t+1},y^t\right)=\frac{D_y^t\left(x^o,1,b^o\right)\cdot y^{t+1}}{D_y^t\left(x^o,1,b^o\right)\cdot y^t}=\frac{y^{t+1}}{y^t} \tag{3}$$

By following the same procedure as above for the bad output, starting with the distance functions defined for the bad output sub-vector between time periods t and $t+1$, and contracting bad output, we arrive at the following bad output quantity index:

$$Q_b^t\left(b^{t+1},b^t\right)=\frac{D_b^t\left(x^o,y^o,1\right)\cdot b^{t+1}}{D_b^t\left(x^o,y^o,1\right)\cdot b^t}=\frac{b^{t+1}}{b^t}, \tag{4}$$

which simply reflects the change in bad output from period t to period $t+1$, holding inputs and good output constant.

Finally, we can specify *EP* as:

$$EP^{t,t+1}\left(y^{t+1},y^t,b^{t+1},b^t\right)=\frac{Q_y^t\left(y^{t+1},y^t\right)}{Q_b^t\left(b^{t+1},b^t\right)}=\frac{y^{t+1}/y^t}{b^{t+1}/b^t}=\frac{y^{t+1}/b^{t+1}}{y^t/b^t}, \tag{5}$$

which credits good output per unit of the bad output. Then, if production of the good (bad) output increases between the time periods t and $t+1$, everything else constant, it will influence $EP^{t,t+1}$ positively (negatively).

From (5) it also clear that *EP* is the growth rate (plus one) of the inverse of the emission intensity index. That is if we define the inverse to the emission intensity as $I_t = y_t/b_t$, then we have:

$$I^t = EP^{t-1,t}\cdot I^{t-1} \tag{6}$$

Dividing both sides of (6) with I^0 gives the environmental performance between time period 0 and t. From equations (5) it is clear that *EP* can be decomposed, into two components. For instance, if a country's *EP* improves it can be investigated whether it is mainly due to an increase in good output or mainly due to a reduction in bad output, or due to a balanced combination of the two.

The fundamentals for our analysis are equations (5) and (6). Given data on good and bad output we can calculate *EP* and *I* to be used in the second step, the convergence analysis.

3. Empirical approach

The empirical analysis is performed in two steps. First we specify and calculate the *EP* index at country level. In the second step we specify a typical "growth equation" with *EP* as the dependent variable and *I* as the independent variable together with other control variables, such as capital and fossil fuels use. The choice of controls is based on production theory where each production process depends on a given technology that combines effective capital, energy and labor services to produce a unit of output and in the process of converting the inputs (effective capital and energy) also generate pollution. This production process at the firm level can be aggregated to the macro-level to provide aggregate output and emissions levels that are generated from input combination via a given level of technology. We therefore assume environmental performance to depend on the inverse of the initial emission intensity, capital and fossil fuel use, where fossil fuels is used as a proxy for energy use, since most of the emissions is generated from the use of fossil fuels.

The main focus of this study is to examine the convergence hypothesis, specifically, convergence in *EP* (growth in the inverse of CO_2 intensity) by analyzing a cross-country data than spans a period of over 30 years. Three main approaches are commonly applied to analyses the convergence hypothesis both in the environmental and economic growth literature. In this study, however, we focus on the β-convergence approach in a panel data framework. Formally we specify the basic empirical model as:

$$\begin{aligned} &\ln EP_{i,t} = \alpha_i + \phi_t + \beta \ln I_{i,t-1} + \gamma_1 \ln K_{i,t} + \gamma_2 \ln FF_{i,t} + \varepsilon_{i,t}, \\ &i = 1,...N = Countries, \quad t = 1,....T = time\ periods \end{aligned} \tag{7}$$

where β is the convergence parameter (the parameter of our central interest), I_{t-1} is the initial level of the inverse in emission intensity, $\ln K_{i,t}$ is capital in logs and $\ln FF_{i,t}$ is fossil fuel use in logs.[3] Our interest is to test the hypothesis that $\beta < 0$, which, if the hypothesis holds, implies the existence of so-called β-convergence. This means that countries with relatively low level of the inverse of initial emissions intensity (high level of emission intensity) tends to grow faster in terms of environmental performance, and hence tend to catch up with countries that start at a

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[3] Note that this is a year-to-year, panel data specification of convergence. Alternatively we could specify a cross-sectional model that relates the mean of the environmental performance index over a time period to an initial time period intensity level.

higher initial level of inverse of emissions intensity. If this is the case it may be because the low performance countries can benefit from the experience and technologies developed and used by the high performers. We also include time specific effects (ϕ_t) as well as country specific effects (α_i) to account for unobservables that are time specific and country specific, respectively. Thus, if $\beta < 0$, $\alpha_i = \alpha$ for all i, and $\gamma_1 = \gamma_2 = 0$, then we have what has been called absolute convergence, i.e. all countries converges to the same inverse emission intensity level. If the above does not hold true, apart from $\beta < 0$, we have what has been called conditional convergence, which means that the growth paths differs, and hence do not converge to the same emission intensity level.

Further, to allow for more flexibility and to account for heterogeneity in convergence, a more general specification of equation (7) is proposed that can be expressed as;

$$\begin{aligned}\ln EP_{i,t} = \tilde{\alpha}_i + \phi_t + \tilde{\beta} \ln I_{i,t-1} + \tilde{\gamma}_1 \ln K_{i,t} + \tilde{\gamma}_2 \ln FF_{i,t} + \gamma_3 \ln I_{i,t-1} \cdot \ln K_{i,t} + \gamma_4 \ln I_{i,t-1} \cdot \ln FF_{i,t} + \\ \gamma_5 \ln K_{i,t} \cdot \ln FF_{i,t} + \tilde{\varepsilon}_{it}\end{aligned} \tag{8}$$

The convergence parameter, corresponding to β in equation (7), is then found by taking the partial derivative of equation (8) with respect to the inverse of the initial emission intensity. Correspondingly the effect on EP from the level of fossil fuel use is the derivative with respect to fossil fuel use:

$$\frac{\partial \ln EP_{it}}{\partial I_{i,t-1}} = \tilde{\beta} + \gamma_3 \ln K_{it} + \gamma_4 \ln FF_{i,t}$$

$$\frac{\partial \ln EP_{it}}{\partial \ln FF_{it}} = \tilde{\gamma}_2 + \gamma_4 \ln I_{i,t-1} + \gamma_5 \ln K_{it}.$$

As a result, using equation (8) allows the rate of convergence to vary between countries due to differences in capital intensity and fossil fuel use.

The specifications, as presented in equation (7) and (8), are estimated using a fixed effects model (time and country) due to the following reason. Firstly, we do not think that country specific unobservables, such as norms or culture, are uncorrelated with the explanatory variables such as the inverse of emissions intensity or capital. It is most likely that norms and culture influence how policies are adopted to influence capital accumulation and its association with labor and the combination of this on output-emissions relations. Secondly, given the long time period, times series proprties cannot be ignored. We assess this via various diagnostic tests on the residual to check for stationarity and also check for cross-sectional dependence. We also include time fixed effects that can capture common factors that are time specific since it otherwise could lead to spillover effects (cross-sectional dependence), which may lead to biased estimates in either direction. It is important to clarify that the time fixed effects cannot account for all forms of common factor effects, but only for time specific common factors.

4. Data

The data used for the analysis is a panel data set covering 1971 to 2008 for 94 countries (list of the countries is presented in Table A1 in the appendix) and includes data on CO_2 emissions in kilo tons, gross domestic product (GDP) in constant 2000 US dollars, gross fixed capital as a ratio of GDP, total fossil fuels as a ratio of total energy use. All variables are taken from the World Development Indicator (WDI) database of the World Bank. The CO_2 data together with the GDP are used to calculate, or construct, the environmental performance index.

The CO_2 data were originally gathered and developed by Marland et al. (1989), and were constructed as estimates of CO_2 emissions from fossil burning and manufacturing of cement. This method was adopted by the World Bank in the construction of the recent CO_2 series. One shortcoming of this data series is that it omits carbon dioxide emissions stemming from deforestation, land-use changes, and the burning of wood fuel. But irrespective of this, we think this variable is reliable, and most of all consistent across the world and can reasonable approximate global CO_2 emissions despite an error of uncertainty of 6-10% (Strazicich and List, 2003).

The data on capital is constructed based on capital investments that include plant, machinery and equipment purchases, land development, rail and road constructions, buildings, and net acquisition of valuables. The capital variable is expressed as a ratio of GDP. It is possible that some of the variables included in the construction of the capital stock might not directly require energy services in their use but might do so in their production and therefore their contribution to CO_2 emissions might be due to both processes (consumption and production).

Fossil fuel data comprises of coal, oil, petroleum, and natural gas products, expressed as a ratio of total energy use. Total energy use data is constructed from primary energy use that includes indigenous production plus imports and stock changes, and excludes exports and fuels supplied to ships and aircraft engaged in international transport. It is expressed in kilo tons of oil equivalents.

Summary statistics for the variables used for the analysis, which is presented in Table 1, reveals a large variation between countries for all variables. The variability of each of the variables is shown by the standard deviation with large values indicating more variability. Furthermore, we calculated the cumulative *EP* (geometric mean) and its two components (good output and bad output) and presented in figure 1. The figure indicates that before 1990, changes in bad output (cumulative) tend to dominate changes in good output and consequently result in lower environmental performance in relative terms. However, after 1990, the changes in bad output is lower relative to changes in good output and implies higher environmental performance, which appear to indicate decoupling between GDP (good output) and CO_2 (bad output) after the 1990s.The implication of this is that over the years, both production and consumption technologies have either become more efficient in the use of fossil energy, or that a shift has occurred towards more use of non-fossil energy, or both.

Table 1. Summary statistics for 94 countries, 1971-2008.

Variable	Obs	Mean	Std. Dev.	Min	Max
CO_2 (in 1000)	3570	189.3656	631.0257	.022002	7035.444
GDP (in 1000)	3572	273074.9	810098.5	448.0554	9532562
Fossil energy (in 1000)	3562	59.94908	203.7318	0.060494	2000.829
Capital (% GDP)	3494	21.70239	6.285652	2.000441	60.56181
EPI	3476	1.010893[4]	.1476797	.2634722	4.322163

The world GDP series also depicts a positive trend over the period under study, implying that at the global level the world is producing more goods and services over time, which then put more pressure on the use of energy, especially fossil energy with consequences on CO_2 emissions. However, the gap between the mean GDP series and that of CO_2 widens over time. This relationship provides some evidence of a decoupling between CO_2 and GDP. The upper panel in figure 1 also reveals a positive relationship between GDP and the CO_2 series but with different slopes, implying that other factors in addition to GDP influences the trend dynamics of global CO_2 emissions.

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[4] Is the geometric mean

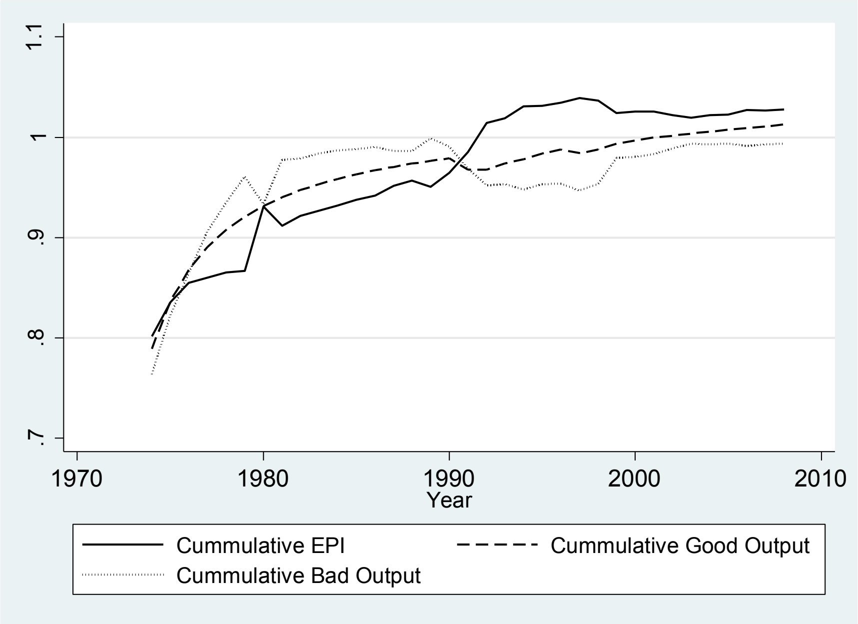

Figure 1: Cummulative *EP* and its components (good output and bad output)

5. Results

Given the construction, or calculation, of the *EP* and the inverse of the emission intensity index according to equations (5) and (6), the empirical strategy in our analysis follow a two-step procedure: firstly, we will estimate equation (7) using the whole panel to examine the *β*-convergence hypothesis, while allowing for heterogeneity in the convergence parameter via interaction terms between previous *I*, *K*, and *FF* (inverse in emission intensity, capital and share of fossil fuel use); secondly, we divide the sample into three groups of countries (low income, middle income and high income) based on per capita income levels consistent with the World Bank classification. The idea is to assess if the test for *β*-convergence is sample dependent, and to examine possible heterogeneity in *β*-convergence in line with the so call "club" convergence by testing if countries with different per capita income levels converge differently or otherwise.

The results presented in Table 2 is based on the global sample, where we first test for unconditional *β*-convergence by estimating equation (7) and (8) with the restriction that $\alpha_i = \alpha$ for all i and $\gamma = 0$. The results for the unconditional *β*-convergence are presented in column (1) in Table 2. The estimated coefficient of the inverse in the initial emission intensity (the *β*-convergence) parameter is negative and significant at the 5% level. The implication of this result is that, countries that starts at a lower level of the inverse in the initial emission intensity tends to grow faster in their environmental performance than countries that start at higher level and that this difference only depend on the initial level of the inverse in emission intensity and nothing else. Intuitively, this unconditional β-convergence hypothesis appears very restrictive in the sense that we think that other important factors also influence the differences in the rate of *EP*. For instance differences in the amount of fossil fuels usage in the production process should have consequences on *EP* for countries (even if we control for the existing technology).

Table 2: Panel estimates for conditional and unconditional β-convergence (global sample)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
$\ln I_{t-1}$	-0.0141***	-0.182***	-0.224***	-0.227***	-0.266***	-0.302***	-0.252***
	(0.003)	(0.020)	(0.041)	(0.046)	(0.058)	(0.059)	(0.042)
$\ln K$		-0.001	-0.105	-0.002	-0.100	-0.318**	-0.312**
		(0.013)	(0.089)	(0.012)	(0.088)	(0.107)	(0.108)
$\ln FF$		-0.097***	-0.098***	-0.139***	-0.138***	-0.209***	-0.159***
		(0.015)	(0.015)	(0.038)	(0.038)	(0.044)	(0.025)
$\ln I_{t-1}*\ln K$			0.014		0.013	0.021	0.022
			(0.012)		(0.012)	(0.012)	(0.012)
$\ln I_{t-1}*\ln FF$				0.005	0.005	0.006	
				(0.004)	(0.004)	(0.004)	
$\ln K*\ln FF$						0.019***	0.018**
						(0.006)	(0.006)
Time Dummies	yes	yes	yes	yes	yes	yes	yes
Constant	0.097***	CFF	CFF	CFF	CFF	CFF	CFF
	(0.027)						
Test (α_i=α)		2.78	2.75	2.83	2.81	2.89	2.84
		[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
Test (γ=0)		31.93	22.13	21.31	16.63	13.41	16.74
		[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
CV	0.0162	0.01394	0.01392	0.01397	0.01395	0.01389	0.01386
AR1-Test	-2.91	-2.58	-2.59	-2.60	-2.61	-2.64	-2.63
	[0.003]	[0.009]	[0.009]	[0.009]	[0.009]	[0.008]	[0.008]
AR2-Test	-0.46	0.44	0.46	0.47	0.48	0.48	0.46
	[0.644]	[0.656]	[0.645]	[0.640]	[0.631]	[0.629]	[0.644]
CD-Test	2.20	1.73	1.71	1.80	1.79	2.02	1.92
	[0.028]	[0.085]	[0.087]	[0.072]	[0.073]	[0.043]	[0.055]
Unit root Test	*I*(0)	*I*(0)	*I*(0)	*I*(0)	*I*(0)	*I*(0)	*I*(0)
N	3476	3395	3395	3395	3395	3395	3395

Standard errors in parentheses (robust standard errors) and *P*-values in square brackets, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, CFF denotes country fixed effects, AR1-Test is first order serial correlation test, AR2-Test is second order serial correlation test, CD-test is the cross-sectional dependence test base on Pesaran (2004) test for the Null of cross-sectional independent residuals and N is the number of observations.

Next we proceed to test the restrictions imposed in estimating the unconditional β-convergence model by relaxing the restriction that $\alpha_i = \alpha$ for all i and $\gamma = 0$. The results are reported in columns (2) to (7), with column (2) allowing for country specific constants with additional regressors (capital and fossil fuel use). Columns (3)-(6) are models that allows for various combinations of interactions between the initial inverse in emission intensity, capital and fossil fuel, while column (7) reports the results for a model that adds interaction between fossil fuel use and capital to the model in column (3). The test that $\alpha_i = \alpha$ is rejected for each of the models presented in column (2) to (7), also the test that $\boldsymbol{\gamma} = 0$ is rejected at the 5% level of significance, implying that the unconditional β-convergence is not appropriate in exploring the β-convergence hypothesis for this study. Henceforth we will therefore focus on the conditional β-convergence hypothesis. However in order to discriminate between the conditional β-convergence models, we apply cross-validation (CV) criteria to the models presented in columns (2) to (7) and base our conclusions on the model with the smallest CV value as well as correcting for cross-section dependence. The CV values show little differences but indicate that the model presented in column 7 has the smallest CV value and also the errors do not suffer from cross-sectional dependence at the 5% significance level, hence we focus our interpretation on the results presented in column 7 in Table 2.

The results from the preferred model indicate evidence of conditional β-convergence in environmental convergence, as the coefficient of the inverse of the initial emission intensity is significantly negative. Further, the results indicates that the convergence parameter does not vary with the level of capital for the global sample, since the coefficient of the interaction term between the inverse of the initial emission intensity and that of capital is insignificant. The capital elasticity is -0.3, which is significant at the 5% level and implies that capital, on average, tend to reduce environmental performance. The implication of this is that the carbon energy conservation investments that have been undertaken are not large enough to offset the additional amount of carbon that is needed for having more capital, and as a consequence the energy requirements outweigh the energy saving potentials from these investments.

The estimated effect on *EP* from the fossil fuel share, on the other hand, depends on the capital stock since the interaction effect is statistically significant. The fossil fuel share elasticity is then calculated by taking the partial derivative of *EP* with respect to the fossil fuel share, which then varies over time and across country due to variation in the capital stock over time and between countries. Figure 2 present the graph for the average global fossil fuel share elasticity, and it shows variation from -0.21 to -0.02 for the period under study. The implication of this is that, *EP* appears to be less responsive to changes in the global average fossil fuel share in 2008 relative to say 1971. One possible interpretation of this is that even if the share of fossil fuels increases on average, its effect on *EP* has become smaller due to improvements in energy efficiency/productivity. That is, more good output (y) for the same amount of bad outbut (b).

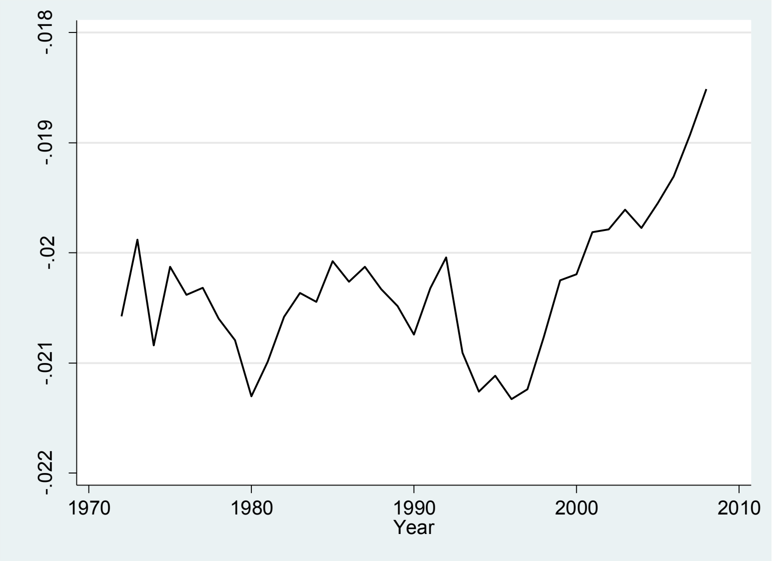

Figure 2: Estimated Global Average Fossil fuel elasticity for the period 1971 to 2008

The time series properties for the preferred model are also analyzed. The reason is that given the long time period dimension we cannot ignore time series properties such as unit roots in the model's residuals, cross-sectional dependence (spillover effects), and serial correlation. The preferred model, however, turn out to perform well on all the time series diagnostics. We apply three different panel unit root tests (Maddala and Wu, 1999, Im et al., 2003, and Pesaran, 2007) on the model residuals with and without trend. The results from these tests consistently reject the null of unit root, implying that the model residuals are *I*(0), which is consistent with the concept of cointegration and non-spurious regression. Further, we apply the CD-test proposed by Pesaran (2004) for cross-sectional dependence. The test result from this could not reject the null hypothesis of cross-sectional independence of the residuals at the 5% significant level, implying no cross-sectional dependence in the preferred model. Additionally, the model is free from second order serial correlation as the *P*-value of the test statistic indicates that the null hypothesis of no second order serial correlation cannot be rejected at the 5% significance level.

Heterogeneity based on sub-samples

For the purpose of addressing possible heterogeneity, based on per capita income levels, we estimated equation (7) and (8) on three sub-samples (low income, medium income and high) using the preferred model. The estimated results are reported in Table 3, with the heading of each column indicating each of the sub-samples used. The estimated convergence parameter in each of the sub-samples is negative and significant at the 5% level, implying evidence of conditional convergence. However a chi-square test to check if the differences in the estimated convergence parameter are significant reveals that both the low and middle income samples are significantly different from the high income sample, but the difference between the low and middle income sample is not significant.

Table 3: Panel estimates for conditional β-convergence (sub-samples based on income level)

	(2) Low Income	(3) Middle Income	(4) High Income
$\ln I_{t-1}$	-0.397^{***}	-0.351^{***}	-0.873^{***}
	(0.064)	(0.074)	(0.238)
$\ln K$	0.190	-0.502^{*}	-2.318^{***}
	(0.266)	(0.221)	(0.700)
$\ln FF$	-0.238^{*}	-0.201^{***}	-0.252^{***}
	(0.106)	(0.035)	(0.061)
$\ln I_{t-1} * \ln K$	-0.014	0.039	0.244^{**}
	(0.018)	(0.021)	(0.080)
$\ln K * \ln FF$	-0.014	0.026^{**}	0.043^{**}
	(0.035)	(0.009)	(0.015)
Time Dummies	yes	yes	yes
Country effects	yes	yes	yes
N	361	2349	682
	Equality test for β in the three samples		
Chsq-test ($\beta_{low} = \beta_{middle} = \beta_{high}$)	11.47 [0.000]		
Chsq-test ($\beta_{low} = \beta_{middle}$)	0.24 [0.623]		
Chsq-test ($\beta_{low} = \beta_{high}$)	4.16 [0.041]		
Chsq-test ($\beta_{middle} = \beta_{high}$)	4.83 [0.027]		

Standard errors in parentheses, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, we also tested the equality of β (the coefficient for lnI_{t-1}) across the three sub-samples by combining the three estimates that allows for testing restrictions across different samples using chi-square test (the suest command in STATA allows for the combination of estimates across different samples), where Chsq is chi-square and the P-values in square brackets.

Moreover, we find that the interaction term between capital and the inverse of initial emission intensity to be significant only for the high income sample. The results are thus revealing heterogeneity at the country level within the high income group (since the partial derivative of EP with respect to the inverse of initial emission intensity depends on the level of capital). The estimated rate of convergence for low income and middle income groups are -0.40 and -0.35, respectively. In the case of the high-income group, the estimated rate of convergence is given by $\partial \ln EP / \partial \ln I = -0.873 + 0.244 \cdot \ln K_{i,t}$, which varies with time and over country, since capital varies across country and time. Evaluated at the mean for ln$K$, the convergence rate becomes -0.12, which indicates a slower a slower convergence rate on average for the richest countries. By averaging over countries figure 3 presents the average variation over time for the rate of convergence in the high-income sample. Figure 2 reveals small variability over time, ranging from -0.10 to -0.14. However, if we instead calculate the variation over countries, by taking averages over time, the variation increases and range from -0.04 to -0.17 (results are presented in Table A2 in the appendix), implying differences in convergence is higher between countries than over time for the high income countries.

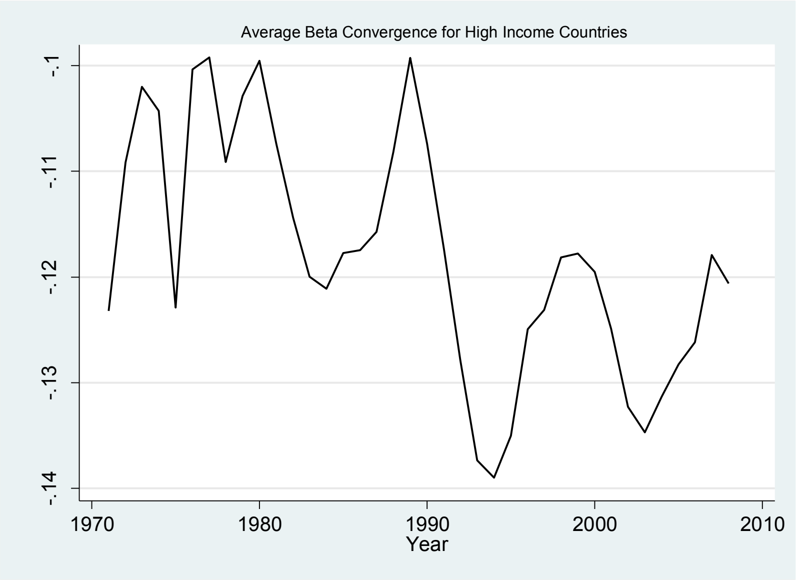

Figure 3: Graph for β-convergence for high income countries

The results further show that the capital share does not have a significant effect on environmental performance for the low income countries. This might be explained by both the size and type of capital used by this group of countries. It is likely that most of the capital in the low income countries do not require much energy services, partly due to geography and partly due to affordability. For instance, buildings in most low income countries do not have electric cookers, washing machines, heating/air conditions, which imply less energy use per house relative to the high income countries. In addition, the size of capital in low income countries is small relative to that of the high income countries. The estimates based on the middle and high-income samples indicate on the other hand a significant effect of capital, which varies with the inverse of the initial emission intensity. The graph for the average capital elasticity for both the middle and high-income group is presented in Figure A1 in the appendix, and shows variation over time as expected.

We also find that the fossil fuel elasticity vary over the level of capital for both the middle and high-income samples, consistent with the global model. However, in the case of the low-income sample we find no evidence of variation over the level of capital, since the interaction term for fossil fuel use and that of capital is insignificant at the 5% level. The fossil fuel elasticity for the low-income sample is -0.24, which implies fossil fuel usage tend to have a negative impact on environmental performance. We also calculated the average middle and high income fossil fuel elasticity and these are presented in Figure 4. As can be seen, the elasticity is lower on average, and varies slightly over time. One possible explanation to the difference in fossil fuel share elasticity between low and high income countries is that high income countries have a more carbon efficient technology, i.e. more good output can be produced for the same amount of bad output.

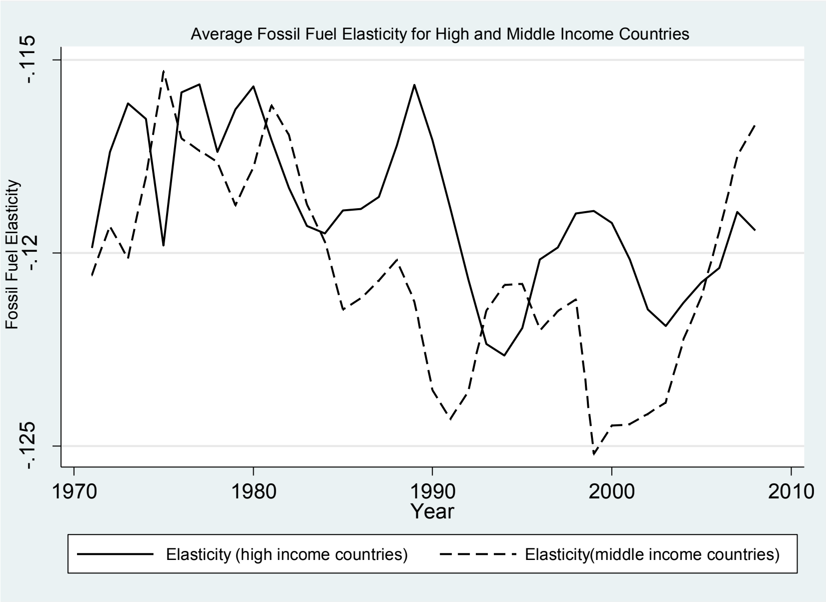

Figure 4: Estimated average fossil fuel elasticity for middle and high income samples

Additionally, we also examine the effect of the Kyoto protocol on *EP* by including a dummy for the Kyoto implementation period in equation (8). The results are reported in Table A3 in the appendix and indicate evidence of a significant positive effect of Kyoto on *EP* for both the global sample and each of the sub-samples. However, the results based on the sub-sample reveal that the shifts are higher for the low and middle income countries in comparison to the high income countries, irrespective of no specific binding commitments for the low income countries. As a robustness check on the construction of the Kyoto dummy, we also used a different dummy that consider both the implementation and signing period for the protocol (the signing of the Kyoto protocol was in 1997, while its implementation takes effects in 2005). We did not, however, find any significant differences in the results, hence we decided to only report the results based only on the implementation period.

From the results above we can draw a number of overall conclusions. Firstly, there is strong evidence of conditional convergence in environmental performance (*EP*) on the global scale. Secondly, in general, there is evidence of heterogeneity in convergence in *EP* both between groups of countries, based on income level, and between countries within the high income group. Thirdly, both the share of capital and the share of fossil fuel use tend to have a negative effect on environmental performance, particularly for the middle and high income countries. To achieve better *EP* more effort seems to be needed in both reducing the share of fossil fuels and to increase the use of more energy efficient capital in both production and consumption processes in the economy.

A potential important corollary from the results above is that the abatement costs, due to a relative fast transition to a lower global emission path, may become very high and also vary substantially between countries depending on the capital intensity and the current dependency on fossil fuels. The reason for this is that if there is a hurry to stabilize the CO_2 concentration level, and hence urgent to quickly reduce emissions, then capital has to be replaced at a faster rate than business as usual. As a result, overall abatement costs will increase, and in the presence of large variations in convergence patterns multi-lateral agreements may be more difficult to achieve. These kinds of difficulties may increase as more countries, especially in Asia, is on a path of fast growth, implying among other things, an increase in capital intensity.

6. Conclusion

Three key issues are addressed in this study. Firstly, we provide a simple framework in the construction of environmental performance (*EP*) based on production theory. The theory provides an easy procedure in constructing an index that does not require much data in terms of the relevant variables to construct the index. Secondly, we address the question of convergence in *EP* at the global level, and thirdly address the question of possible heterogeneity in *EP* both between groups of countries (in line with the so call "club convergence") and between countries.

Our findings can be summarized as follows. First, the simple theory shows that the *EP* index we construct is simply the rate of change in the ratio of the inverse in emission intensity (emission intensity is define as the ratio of CO_2 emission over GDP). This is because the production process is assumed to result in two outputs, a good output (GDP in this case) and a bad output (CO_2). Since our interest is in *EP* in relation to CO_2 emissions, the construction of the index via this approach is appropriate, given that the GDP variable capture most of the good output in the economy and that the CO_2 variable capture most of the CO_2 emissions in producing the good output. The emphasis here is on CO_2 related *EP*, not *EP* in general.

Secondly, based on the constructed *EP* index, we tested both the unconditional and conditional β-convergence hypothesis at the global level. Here we find strong evidence in support of conditional β-convergence in *EP* in the global sample. This finding is consistent with the finding in Brännlund et al. (2014), which finds evidence of convergence in *EP* for Swedish industries and Camarero et al. (2008) based on 22 OECD countries. Further, the results here indicate that the rate of convergence does not vary with capital and fossil fuel when we employ the whole global sample. The results also show a significant negative effect of capital and the use of fossil fuel on *EP*.

Moreover, the results reveal heterogeneity in conditional β-convergence when the data was divided into three sub-samples based on per capita income (low, middle, and high income samples). It further reveals that not only do the rates of convergence vary between groups of countries, but also vary between countries within the high income sample. However, we find no evidence of differences in convergence between countries within the low-income sample. This means that differences in the rate of convergence tend to be more pronounced between countries within the high income group, likely due to the differences in the share of fossil fuels. Furthermore, our findings show that the rate of convergence for the high-income sample varies with the share of the capital stock, with high capital intensity countries having a low rate of convergence to the steady state relative to countries with low capital intensity. This result is new, compared to the findings from previous research in this area. This heterogeneity between countries, and especially the slow convergence rate among countries with abundant capital, may cause severe problems in negotiations over burden sharing. At one hand low income/capital countries will argue that high income/capital countries have a responsibility to reduce emissions more. On the other hand this would imply high abatement costs for those countries since capital has to be scrapped at a much faster rate than the rather slow process in business as usual.

Lastly, the level of the fossil fuel share has a negative effect on environmental performance for each of the samples, but it tends to vary with capital in the case of the middle and high-income countries. Interestingly we also find a significant effect of the Kyoto protocol on *EP*, which reflects significant positive shifts for the periods that the Kyoto protocol came into effect relative to other years.

These findings suggest that we need policies that promote both efficiency and conservation policies in order to improve *EP*, since both fossil fuel use and capital inversely impact *EP*. Additionally, since every production process result in a good output (GDP) as well as a bad output (CO_2), and since most of the CO_2 is generated from the use of fossil fuel, it is important that economic stimulus policies are well balanced with energy conservation policies in order to promote growth without compromising environmental performance. Finally, since there seems to be significant differences concerning the growth path for different groups of countries, as well as differences in the steady state, a global agreement on burden sharing, concerning CO_2 emissions, has to take these differences into account.

Our findings further suggests that investments in energy conservative measures, especially capital investments tend to have positive impact on *EP* after the year 2000 for the high income countries, implying that conservative measures in terms of capital investment are yielding positive results in terms of producing more good output with less bad output. We also see declining capital elasticity over the study period for the middle-income countries. This implies among other things that both middle and high-income countries are able to produce more output with less carbon emission in later years, compared to the earlier years, which translates to improvement in environmental performance across these countries. The finding on the effect of capital intensity in addition to the positive effect of Kyoto protocol complement the finding in Zhou et al. (2010), irrespective of the differences in data set, time period, focus of the study and methodology.

References

Aldy, J.E., 2006. Per capita carbon dioxide emissions: convergence or divergence? *Environmental and Resource Economics* 33,533–555.

Aldy, J. E., 2007. Divergence in state-level per capita carbon dioxide emissions. *Land Economics* 83(3), 353-369.

Brock, W. A., and Taylor, M .S., 2010. The green Solow model. *Journal of Economic Growth* 15, 127–153

Brännlund, R., Lundgren, T., och Söderholm, P. (2014). Convergence of Carbon Dioxide Performance across Swedish Industrial Sectors: An Environmental Index, CERE Working Paper Nr. 2014:10. Centre for Environmental and Resource Economics, Umeå university.

Camarero, M., Picazo-Tadeo, A. J., and Tamarit, C., 2008. Is the environmental performance of industrialized countries converging? A 'SURE' approach to testing for convergence. *Ecological Economics* 66(4), 653-661.

Camarero, M., Picazo-Tadeo, A. J., and Tamarit, C., 2012. Are the determinants of CO_2 emissions converging among OECD countries? *Economic Letters* 118(1), 159-162.

Dinda, S., 2004. Environmental Kuznets curve hypothesis: a survey. *Ecological Economics* 49(4) 431-455.

Ezcurra, R., 2007. Is there cross-country convergence in carbon dioxide emissions? Energy Policy 35, 1363–1372.

Forsund, F. (2009). Good modelling of bad outputs. Review of Environmental and Resource Economics, 1-38.

Färe, R., S. Grosskopf (2003). *New directions: efficiency and productivity*. Kluwer Academic Publishers.

Färe, R., S. Grosskopf , C.A. Pasurka Jr. (2006). Social responsibility: U.S. power plants 1985–1998. *Journal of Productivity analysis* 26, 259-267.

Grossman, G., and Krueger, A., (1991). *Environmental impacts of North American free trade agreement*. National Bureau of Economic Analysis. Technical report

Grossman G. and A. Krueger (1995), 'Economic Growth and the Environment', *Quarterly Journal of Economics* **3**, 53–77.

Im, K., Pesaran, H., and Shin, Y., 2003.Testing for Unit Roots in Heterogeneous Panels, *Journal of Econometrics* 115, 53-74.

Kijima, M., Nishide, K., and Ohyama, A., 2010. Economic models for the environmental Kuznets curve: A survey. *Journal of Economic Dynamics and Controls*, 34, 1187-1201.

Levinson, A., 2002. The ups and downs of the environmental Kuznets curve. In J. List, & A. de Zeeuw (Eds.), *Recent advances in environmental economics*. Northhampton, MA: Edward Elgar Publishing

Lieb, C., 2004. Possible causes of the environmental Kuznets curve: A theoretical analysis. In *European University Studies, Series V: Economics and Management* Lang, New York.

Maddala, G.S., Wu, S., 1999. A comparative study of unit root tests with panel data and a new simple test. *Oxford Bulletin of Economics and Statistics* 61, 631–652 (special issue).

Marland, G. et al., 1989, *Estimates of CO2 Emissions from Fossil Fuel Burning and Cement Manufacturing,Based on United Nations Energy Statistics and the U.S. Bureau of Mines Cement Manufacturing Data*. ORNL, Oak Ridge, Tennessee.

Nguyen, P., 2005. Distribution dynamics of CO2 emissions. *Environmental and Resource Economics* 32, 495–508.

Olsthoorn, X., Tyteca, D., Wehrmeyer, W., Wagner, M., 2001. Environmental indicators for business: a review of the literature and standardisation methods. *Journal of Cleaner Production* 9, 453–463

Panopoulou, E. and Pantelidis, T.,2009. Club convergence in carbon dioxide emissions. *Environmental and Resource Economics* 44(1), 47-70.

Pesaran, M. H.,2004.General Diagnostic Tests for Cross Section Dependence in Panels, Cambridge Working Papers in Economics No. 0435, University of Cambridge,June 2004.

Pesaran, M. H., 2007. A simple panel unit root test in the presence of cross-section dependence, *Journal of Applied Econometrics* Vol. 22, No. 2, pp. 265-312.

Picazo-Tadeo, A., García-Reche, A., 2007.Whatmakes environmental performance differs between firms? The case of the Spanish tile industry. *Environment and Planning* 39, 2232–2247.

Ramanathan, R., 2002. Combining indicators of energy consumption and CO2 emissions: a cross-country comparison. *International Journal of Global Energy Issues* 17, 214–227.

Shephard, R.W., 1970. *Theory of Cost and Production Functions*. Princeton University Press, Princeton.

Stegman, A. and W. J. McKibbin. 2005. Convergence and Per Capita Carbon Emissions. *Brookings Discussion Papers in International Economics*, No. 167.

Stern, D.I., 2004. The rise and fall of the environmental Kuznets curve. *World Development* 32(8), 1419-1439.

Strazicich, M.C., List, J.A., 2003. Are CO_2 emissions levels converging among industrial countries? *Environmental and Resource Economics* 24, 263–271.

Tyteca, D., 1996. On the measurement of the environmental performance of firms: a literature review and a productive efficiency perspective. *Journal of Environmental Management* 46, 281–308.

Westerlund, J., Basher, S.A., in press. Testing for convergence in carbon dioxide emissions using a century of panel data. Environmental and Resource Economics.

Zaim, O., Taskin, F., 2000. Environmental efficiency in carbon dioxide emissions in the OECD: A non-parametric approach. *Journal of Environmental Management* 58, 95–107.

Zaim, O., 2004. Measuring environmental performance of state manufacturing through changes in pollution intensities: a DEA framework. *Ecological Economics* 48, 37–47.

Zofio, J.L., Prieto, A.M., 2001. Environmental efficiency and regulatory standards: The case of CO2 emissions from OECD. *Ecological Economics* 48, 37–47.

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

Zhou,P., Ang, B.W,, Han,J.Y., 2010. Total factor carbon emission performance: A Malmquist index analysis. *Energy Economics* 32, 194-201.

Appendix

Table A1: List of Countries for the Study

Albania
Algeria
Angola
Argentina
Australia
Austria
Bahrain
Bangladesh
Belgium
Benin
Bolivia
Botswana
Brazil
Bulgaria
Cameroon
Canada
Chile
China
Colombia
Congo. Dem. Rep.
Costa Rica
Cuba
Denmark
Dominican Republic
Ecuador
Egypt. Arab Rep.
El Salvador
Finland
France
Gabon
Germany
Ghana
Greece
Guatemala
Honduras
Hungary
India
Indonesia
Iran. Islamic Rep.
Iraq
Ireland
Israel
Italy
Jamaica
Japan
Jordan
Kenya
South Korea.
Kuwait
Lebanon
Libya
Malaysia
Mexico
Morocco
Mozambique
Nepal
Netherlands
New Zealand
Nicaragua
Nigeria
Norway
Oman
Pakistan
Panama
Paraguay
Peru
Philippines
Poland
Portugal
Qatar
Romania
Saudi Arabia
Senegal
Singapore
South Africa
Spain
Sri Lanka
Sudan
Sweden
Switzerland
Syrian Arab Republic
Tanzania
Thailand
Togo
Tunisia
Turkey
United Kingdom
United States
Uruguay
Venezuela. RB
Vietnam
Yemen. Rep.
Zambia
Zimbabwe

Table A2: Estimated β-convergence for high income countries average over time

Country	β- Coefficient	Country	β-Coefficient
Australia	-0,077	Japan	-0,069
Austria	-0,102	South Korea	-0,041
Belgium	-0,134	Kuwait	-0,169
Canada	-0,130	Netherlands	-0,126
Chile	-0,127	New Zealand	-0,119
Denmark	-0,138	Norway	-0,106
Finland	-0,122	Portugal	-0,092
France	-0,145	Singapore	-0,047
Germany	-0,129	Spain	-0,079
Greece	-0,109	Sweden	-0,150
Ireland	-0,119	Switzerland	-0,101
Israel	-0,143	United Kingdom	-0,174
Italy	-0,127	United States	-0,157

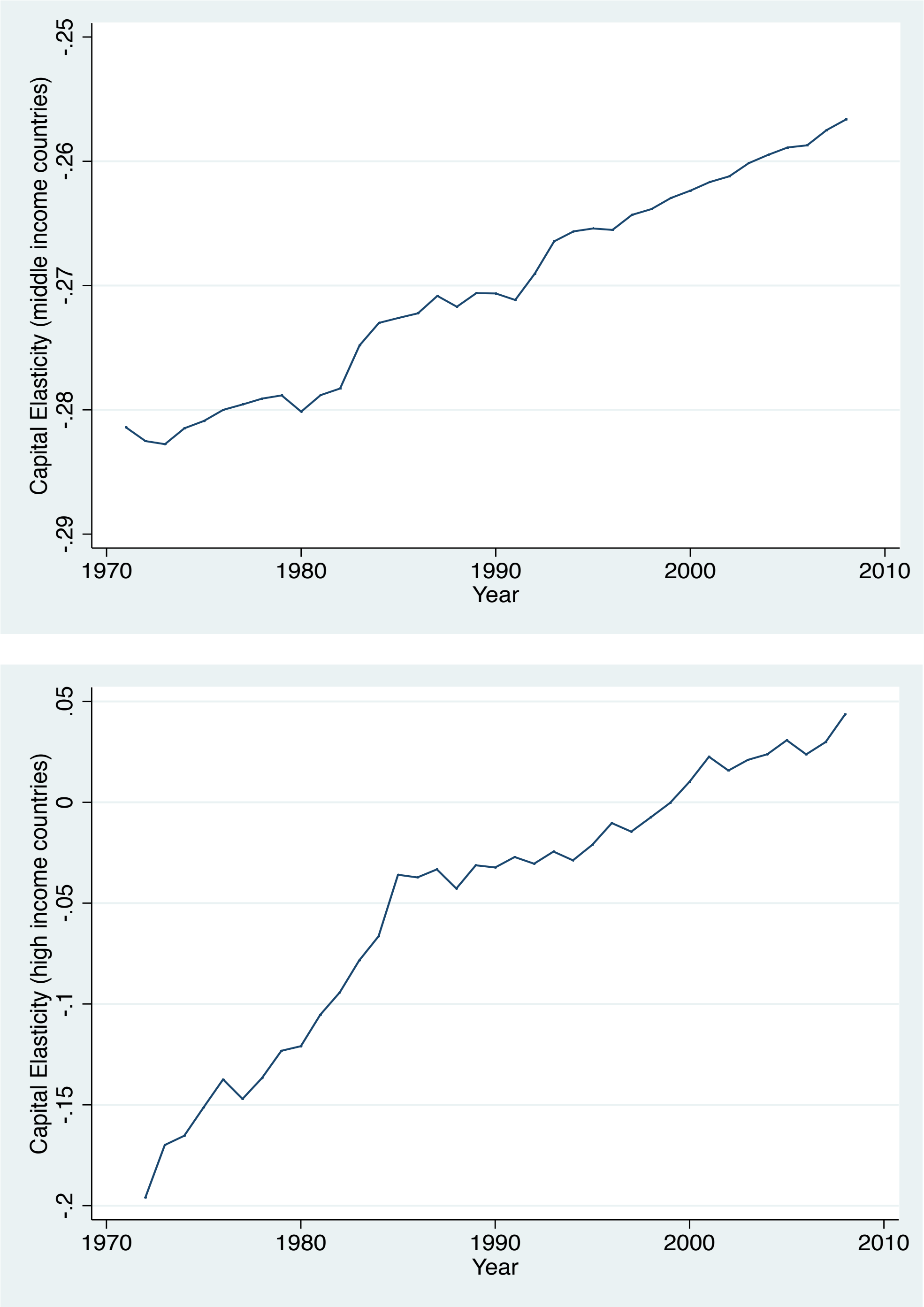

Figure A1: Graph for capital elasticity for middle and high income Countries, calculated as $\frac{\partial \ln EPI}{\partial \ln K} = -0.502 + 0.026 \times \frac{1}{N_m} \text{lnff}_{i,t}$ and $\frac{\partial \ln EPI}{\partial \ln K} = -2.318 + 0.244 \times \frac{1}{N_h} \ln I_{i,t-1} + 0.043 \times \frac{1}{N_h} \text{lnff}_{t}$, respectively.

Table A3: Estimates for the impact of Kyoto on environmental performance

	(1) Full Sample	(2) Low-Income	(3) Middle-Income	(4) High-Income
$\ln I_{t-1}$	-0.252^{***}	-0.397^{***}	-0.351^{***}	-0.873^{***}
	(0.042)	(0.064)	(0.074)	(0.238)
$\ln K$	-0.312^{**}	0.190	-0.502^{*}	-2.318^{***}
	(0.108)	(0.266)	(0.221)	(0.700)
$\ln FF$	-0.159^{***}	-0.238^{*}	-0.201^{***}	-0.252^{***}
	(0.025)	(0.106)	(0.035)	(0.061)
$\ln I_{t-1}*\ln K$	0.0221	-0.0142	0.0398	0.244^{**}
	(0.012)	(0.018)	(0.021)	(0.080)
$\ln K*\ln FF$	0.0184^{**}	-0.0149	0.0262^{**}	0.0432^{**}
	(0.006)	(0.035)	(0.009)	(0.015)
kyoto	0.177^{***}	0.235^{***}	0.200^{***}	0.115^{*}
	(0.023)	(0.064)	(0.029)	(0.049)
Time Dummies	yes	yes	yes	yes
cons	3.025^{***}	4.361^{***}	4.066^{***}	9.298^{***}
	(0.416)	(0.842)	(0.763)	(2.270)
N	3395	361	2349	682

Standard errors in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$