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The effect of including the environment in the neoclassical growth model

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Abstract

This study begins with an exposition of basic principles of the theory of Optimal Control as this is used in the development of the theory of Economic Growth. Then, a brief presentation of the Neoclassical Model of Economic Growth follows and two applications are presented. In the first, optimal control techniques are used, in the context of neoclassical growth, to maximize the representative household's total intertemporal welfare. In the second, the same problem is posed with two additional variables that affect welfare in opposing ways: *pollution* and *abatement expenditures*. In both applications, the *optimal steady-state conditions* are derived. This allows for a preliminary comparison of the resulting *balanced growth paths* under the criterion of welfare maximization with and without environmental externalities. Finally, using a balanced panel data of 43 countries and for the time period 1990-2011 we test the validity of including the environment in the neoclassical growth model approximating pollution abatement with the electricity production from renewable sources and pollution with carbon dioxide emissions. With the help of adequate econometric panel data methods we test the validity of the environmental Kuznets curve hypothesis for the full sample, as well as for the OECD and non-OECD countries.

Keywords: Economic Growth; Physical Capital; Technological Progress; Environment; Pollution.

JEL Classification: C6; O41; O44; Q56; Q58.

1. Introduction

The relationship between economic growth and the environment has received much attention recently. The literature considering this relationship is vast. It covers the theory on growth and natural resources extraction and depletion, explores the impacts of endogenous growth theory and investigates the link between environmental pollution and income.

The advancement of economic growth theory started with the Solow-Swan model (Solow, 1956; Swan, 1956) with exogenous technological progress and growth being considered either with exogenous saving rates as in the Solow-Swan model or with households' consumption and savings optimization models called optimal growth or Ramsey models (Ramsey, 1928; Cass, 1965; Koopmans, 1965). These models were followed by endogenous growth models where the "engine of growth" is either technological progress (Romer, 1990) or human capital accumulation (Lucas, 1988).

Natural resources contribute significantly to production. In the basic form of the neoclassical growth theory the contribution of natural resources in production is completely missing. In 1972 the perception of the Solow-Swan model (with three inputs, namely labor, capital and production methods) was confronted by the report of the Club of Rome "the Limits to Growth" (Meadows et al., 1972). In the report it was predicted that the exhaustion of non-renewable resources will result to the fall down of the global economy and the worldwide collapse of the standards of living. Specifically, the report notified humanity for the damaging influence of uninterrupted and rapid economic growth. More pollution and inappropriate use of non-renewable resources may stop economic growth. The economic growth versus the environment dispute considered the relationship between growth and quality of the environment arguing whether a change in growth is essential in improving environmental quality.

De Bruyn (1992) summarizes the attitudes in this dispute and distinguishes the radical and conditional supporters together with the weak and strong antagonists.¹ Specifically, the radical and conditional supporters of economic growth propose a direct positive relationship between growth and environmental quality. The former believe that growth increases technological innovation requiring more R&D and changes the standards of living resulting in a better quality of the environment. The latter considers growth as a requirement for environmental management raising funds necessary for adoption of appropriate environmental policies (Simon, 1981; World Bank 1992). The weak and strong antagonists consider economic growth as harmful for the environment. The weak antagonists believe that economic growth is associated with more output damages the environment. The reduction in growth of specific polluted economic sectors may be necessary to recover environmental quality (Arrow et al., 1995). Similarly, strong antagonists claim that in the LR growth will be damaging the environment and the way out is to decrease economic growth (Meadows et al., 1972; Daly, 1991).

There are various theories of the relationship between economy and environment. The *limits theory* classifies this relationship in terms of the irreversible damage imposed to the environment hitting a threshold ahead of which production is so defectively influenced that the economy shrinks. The *new toxics view* is based on the idea that pollutants' emissions are reduced with additional economic growth but the new pollutants replacing them are raised. In this way the validity of the calculated turning points is questioned and there is possibility that environmental damage persists to be enhanced as economies develop (Everett et al., 2010). According to the *race to bottom theory* international competition first increases environmental damage up to the point where developed countries begin to decrease their environmental

¹ Different classifications may be found in van den Bergh and Mooij (1999).

effect but at the same time export activities polluting the environment to poorer countries. In this way we may end-up in a non-improving situation. Finally, the *Porter's Hypothesis* considers economic growth and the environment as a false dichotomy. It finds that effective environmental policies may raise the level of R&D into more resource efficient processes, leading to higher competitiveness and profitability (Everett et al., 2010).

Empirical findings of the relationship between economic growth and the environment and the investigation of the environmental Kuznets curve hypothesis are based on model specifications. The environmental Kuznets curve (EKC) hypothesis suggests the existence of an inverted U-shape relationship between environmental damage and per-capita income. Specifically, it relates environment (using environmental pollution or damage as dependent variable) with economic development represented by economic variables (like GDP/c in level, square and cubic values as independent variables). Depending on data availability different variables have been used to approximate environmental damage like air pollutants (SO_x, NO_x, CO₂, PM10, etc.), water pollutants (e.g. toxic chemicals discharged in water, etc.) and other indicators like deforestation, municipal waste, energy use and access to safe drinking water.

This paper is structured as follows. Section 2 discusses the existing theoretical and empirical literature. Sections 3 and 4 present the dynamic models of modern macroeconomic theory together with two applications with the second one referring to the proposed theoretical inclusion of the environment into the neoclassical growth theory.² Section 5 presents data and econometric methods used in the proposed application and the related empirical findings. The final section concludes the paper.

² Brock and Taylor (2005) and Xepapadeas (2005) provide a full mathematical framework in this kind of analysis. Our study, using specific to the neoclassical growth model functional forms, examines the effects of including the environment in this model and tests empirically its validity.

2. Previous work

Reviews and critiques of the EKC studies may be found among others in Arrow *et al.* (1995), Ekins (1997), Ansuategi *et al.* (1998), Stern (1998) and Halkos and Tsionas (2001). The differences in the extracted relationships and in the calculated turning points may be justified by the econometric models' specification and the adoption of static or dynamic analysis (Halkos, 2003). Simultaneously, the addition of more explanatory variables in the model specification influences the estimated relationship. Roca *et al.* (2001) claim that estimated EKC is weaker when using more independent variables apart from income. Empirical evidence is unclear and mixed (Galeotti *et al.*, 2006; He and Richard, 2010; Chuku, 2011).

Various studies have ended up to linear and monotonic relationships between damage and income.³ Akbostanci *et al.* (2009) and Fodha and Zaghdoud (2010) considering the link between income and environment in Turkey and Tunisia respectively, find a monotonically increasing relationship between CO₂ emissions and income. Others have found inverted-U shaped relationships with turning points ranging from higher than \$800 to less than \$80,000, implying a feasible division of environmental damage from economic growth (Grossman and Krueger, 1995; Holtz-Eakin and Selden 1995; Panayotou 1993, 1997; Cole *et al.*, 1997; Stern and Common 2001; Halkos, 2003; Galeotti *et al.*, 2006). He and Richard (2010) for the relationship between CO₂ emissions and GDP in the case of Canada and by using parametric, semi-parametric and non-linear models found weak evidence of the EKC hypothesis.

Stern *et al.* (1996) claim that the mix of effluent has shifted from sulphur and NO_x to CO₂ and solid waste, in a way that aggregate waste is still high and even if per unit output waste has declined, per capita waste may not have declined. Regressing per capita energy consumption on income and temperature gave them an inverted U-

³ López-Menéndez *et al.* (2014) provide a review of the findings of the EKC empirical studies.

shape relationship between energy and income. Energy consumption peaked at \$14600. The authors claim that the results depend on the income measure used. If income in PPP is used, the coefficient on squared income was positive but small and insignificant. If income per capita was measured using official exchange rates, the fitted energy income relationship was an inverted U-shape with energy use peaking at income \$23900.

Other researchers have found *N*-shape relationships (Friedl and Getzner, 2003; Martinez-Zarzoso and Bengochea-Maranchó, 2004; Akbostanci et al., 2009; Halkos, 2012) showing that pollution and the associated environmental damage from economic growth may be a temporary phenomenon (He and Richard, 2010). Grossman and Krueger (1995) and Shafik and Bandyopadhyay (1992) claim that at high-income levels, material use increases in such a way that forms an *N*-shape relationship.

3. Dynamic models of modern Macroeconomic Theory

The *dynamic* models of modern Macroeconomic Theory – and the models of Growth Theory in particular – are concerned with the behavior of aggregate economy through time. In this context, the pattern of private consumption is summarized in, and by, the behavior of the so-called *representative consumer* or *representative household*. Most usually, the consumer is assumed to face an indefinitely large or ‘infinite’ time horizon and needs to determine all per-period consumption expenditures for this horizon.⁴ From each period’s expenditures the consumer derives a certain level of satisfaction or *utility*. The consumer’s objective is to achieve an **intertemporal allocation of expenditures** which, under given constraints, **maximizes** the *present value* of the **infinite sum of per-period utilities**. This total utility is generally expressed by the *intertemporal utility function*

⁴ Alternatively, one may think that individual consumers have finite lifetimes but they care about their descendants’ welfare. Thus, they maximize intertemporal utility for the whole ‘dynasty’.

$$\mathcal{U} = \int_{t=0}^{\infty} e^{-\rho t} U(c_t, k_t, t) dt \quad (1)$$

where c_t is per capita consumption at time t , k_t is per capita (per worker)⁵ physical capital at time t , and t is simply the ‘time variable’.⁶

The typical problem of maximizing intertemporal utility is essentially an *optimal control* problem which can be stated as

$$\max_{c_t} \mathcal{U} = \max_{c_t} \int_{t=0}^{\infty} e^{-\rho t} U(c_t, k_t, t) dt \quad (2)$$

with constraints

$$\frac{dk}{dt} \equiv \dot{k} = V(c_t, k_t, t) \quad (3)$$

$$k_{t=0} = k_0 \quad (4)$$

$$\lim_{t \rightarrow \infty} (e^{-\rho t} k_t) \geq 0 \quad (5)$$

At this point, we note that all variables depend on time and simplify notation by omitting time subscripts whenever time dependence is easily understood. Further, one may discern the following elements.

1. Function $U(\cdot)$ which is called *instantaneous utility function* and measures consumer’s per-period utility. A common in growth models instantaneous utility function is

$$U(c) = \frac{c^{1-\sigma} - 1}{1-\sigma} \quad \sigma > 0, \quad \sigma \neq 1$$

where σ is the inverse of the elasticity of intertemporal substitution in consumption⁷, and

⁵ Population is equal to the number of workers. Thus, the terms *per capita* and *per worker* are used interchangeably.

⁶ The interpretation of all variables originates from Optimal Growth Theory. In this sense, the material herein is an application of the mathematical Theory of Optimal Control to Economic Growth.

2. Function $V(\cdot)$ which depicts **net** per capita investment. The quantity of per capita physical capital evolves through time according to this equation and influences the future productive capacity of the economy. In optimal control theory (differential) equation (3) is often referred to as *transition equation*.

3. ‘Variable’ c , is in actuality a **function of time**. As it is evident from the statement of the problem, c is the ‘variable’ with respect to which the objective function is maximized.⁸ This is why c is referred to as the *control variable* or *decision variable*. In addition, we note that control variable c affects the objective function \mathcal{U} in two ways: First directly, with its own value and second indirectly, by influencing the value of variable k that also enters the objective function.

4. ‘Variable’ k which evolves as a function of time according to differential equation (3). The value of k determines at any time the state of the dynamical system under examination. For this, k is known as the *state variable*.

5. Parameter $\rho > 0$, which expresses the *subjective rate of time preference*. In other words, ρ is a *discount factor* based on which the values of future flows of utility are converted into *present value* terms.

6. Condition (4) which states that the initial value of k during period $t = 0$ is equal to k_0 .

7. Condition (5) which states that at the end of the problem’s time horizon the quantity of per-capita physical capital cannot be negative.

For the solution of the problem given in relations (2)–(5), we form the function known as *present-value Hamiltonian*

$$H = e^{-\rho t}U(c, k, t) + \lambda_k V(c, k, t) \quad (6)$$

⁷ In a stochastic model σ is also the (constant) *coefficient of relative risk aversion*.

⁸ For mathematical accuracy note that $U(\cdot)$ is a function of the functions k_t and c_t . Thus, $U(\cdot)$ is **not** treated as an ordinary function of real numbers k and c , but as a ‘function of functions’ or *functional*.

As its name implies, equation (6) measures units of utility expressed in present value terms (time period 0). The new term in equation (6) is the ‘variable’ λ_k . This term (also a function of time) is called the *co-state variable*. It measures the *value of extra units of utility* that will be generated by an additional unit of per capita physical capital at time t , when this value is expressed in units of utility of the initial time period (time 0).⁹

Necessary conditions for optimization are

$$\frac{\partial H}{\partial c} = 0 \quad (7)$$

$$\frac{\partial H}{\partial k} = -\dot{\lambda}_k \quad (8)$$

$$\text{όπου } \dot{\lambda}_k \equiv \frac{d\lambda_k}{dt}.$$

$$\frac{\partial H}{\partial \lambda_k} = \dot{k} \quad (9)$$

$$\lim_{t \rightarrow \infty} (\lambda_k k) = 0 \quad (10)$$

Equation (10) is known as *transversality condition* and is necessary for optimality, as it precludes the possibility of *dynamic inefficiency*.¹⁰ It ensures that as we approach at the end of the problem’s horizon it must be either $k = 0$, or $\lambda_k = 0$. The essence of this condition is that either no quantity of physical capital exists, or that any remaining quantity offers zero utility in present value terms (expressed in units of utility at time $t = 0$).

⁹ In other words, λ_k expresses the *present-value shadow price* of k .

¹⁰ This term characterizes an economy that in *steady state (dynamic long-run equilibrium)* ‘over-accumulates’ physical capital, or simply, ‘saves too much and consumes too little’. Such a steady state is **not optimal** as a reduction in the level of physical capital could increase consumption and, therefore utility, for **all** consumers and in **all** time periods.

Typically, it is preferable for further analysis to obtain the solution of the problem as a system of *autonomous* differential equations.¹¹ Aiming at that, we write H as

$$H = e^{-\rho t} \left[U(c, k, t) + e^{\rho t} \lambda_k V(c, k, t) \right] \quad (11)$$

Next we define the *current-value Hamiltonian* as

$$\mathcal{H} = e^{\rho t} H$$

which yields

$$\mathcal{H} = U(c, k) + \mu_k V(c, k, t) \quad (12)$$

Note that $\mu_k = e^{\rho t} \lambda_k$ is the *current-value shadow price* of k . It measures the value of extra units of utility that will be generated by an additional unit of per capita physical capital at time t , when this value is expressed in units of utility **also** at time t . The first-order conditions now become

$$\frac{\partial \mathcal{H}}{\partial c} = 0 \quad (13)$$

$$\frac{\partial \mathcal{H}}{\partial k} = \rho \mu_k - \dot{\mu}_k \quad (14)$$

$$\frac{\partial \mathcal{H}}{\partial \mu_k} = \dot{k} \quad (15)$$

$$\lim_{t \rightarrow \infty} (\lambda_k k) = \lim_{t \rightarrow \infty} e^{-\rho t} \mu_k k = 0 \quad (16)$$

Notice that the right side of (16) implies that the current value of an additional unit of k , that is μ_k , must be either finite or grow at a rate less than $\rho > 0$, so that the discount factor $e^{-\rho t}$ confines the present value of k to zero.

¹¹ In equations of this kind the time variable t , does **not** enter the function as a separate argument.

Now, a useful extension would be to assume that population increases at a constant exogenous rate $\gamma_{\{L\}} \equiv n > 0$. This implies that $L_t = L_0 e^{nt}$ where all symbols have the usual meaning. Based on the above, one can write the optimization problem as

$$\begin{aligned} \max_c \int_{t=0}^{\infty} e^{-\rho t} U(c, k) L_t dt &= \max_c \int_{t=0}^{\infty} e^{-\rho t} U(c, k) L_0 e^{nt} dt \simeq \\ &\simeq \max_c \int_{t=0}^{\infty} e^{-(\rho-n)t} U(c, k) dt \end{aligned} \quad (17)$$

This change does not alter the optimality conditions as the final expression in (17) results from the original after dividing by the constant L_0 . The latter is initial population size (period $t = 0$), which with appropriate *normalization* can be set equal to one.

The important new element is that the discount rate of the modified problem, $\rho - n > 0$, is smaller by n compared to the original. As a result, with an increasing population it is desirable that present generations reduce the rate at which they convert future utility values into equivalent current ones.¹² Such a decision will enable higher savings/investments for the creation of new units of physical capital to be used by future generations. Finally, note that the current value shadow price of k is equal to $\mu_k = e^{(\rho-n)t} \lambda_k$. Conditions (13) and (15) remain the same, while conditions (14) and (16) become

$$\frac{\partial \mathcal{H}}{\partial k} = (\rho - n) \mu_k - \dot{\mu}_k \quad (18)$$

and
$$\lim_{t \rightarrow \infty} (\lambda_k k) = \lim_{t \rightarrow \infty} e^{-(\rho-n)t} \mu_k k = 0 \quad (19)$$

¹² This implies that current generations must decrease their 'impatience' and, in a sense, 'shorten' the perceived distance between current and future values.

Now, observe that the right side of (19) implies that the current value of an additional unit of k , must be either finite or grow at a rate less than $\rho - n > 0$. In such case, the discount factor $e^{-(\rho-n)t}$ would restrict the present value of k to zero.

4. The Neoclassical Model of Economic Growth: A Brief Overview

The neoclassical model has been a cornerstone for the development of modern economic growth theory. It is founded on two basic equations: *the production function* and *the equation of physical capital accumulation*. The production function describes the way *factors of production* or *production inputs* can be combined to produce the economy's final output.¹³ Factors of production are grouped in two broad categories: *labor*, L , and *physical capital*, K . The latter includes tools, machinery, and facilities (plant and equipment) used in production.¹⁴ The production function is of *Cobb-Douglas* form with Constant Returns to Scale (CRS). Denoting total output by Y , it is

$$Y \equiv F(L, K) = L^\alpha K^{1-\alpha}, \quad 0 < \alpha < 1 \quad (20)$$

The labor force, L , coincides with population which is, at present, constant.

Note that the production function (20), satisfies the principle of *positive and diminishing marginal products*, as it is

$$F_L(\bullet) \equiv \frac{\partial F(\bullet)}{\partial L} = \frac{\alpha K^{1-\alpha}}{L^{1-\alpha}} > 0, \quad F_{LL}(\bullet) \equiv \frac{\partial^2 F(\bullet)}{\partial L^2} = -\frac{\alpha(1-\alpha)K^{1-\alpha}}{L^{2-\alpha}} < 0$$

and

$$F_K(\bullet) \equiv \frac{\partial F(\bullet)}{\partial K} = \frac{(1-\alpha)L^\alpha}{K^\alpha} > 0, \quad F_{KK}(\bullet) \equiv \frac{\partial^2 F(\bullet)}{\partial K^2} = -\frac{\alpha(1-\alpha)L^\alpha}{K^{1+\alpha}} < 0$$

¹³ It is typical to measure output in value-terms of a single composite good whose price is set equal to 1. Thus, the final good becomes a **measure of comparison of values** for all other goods and services whose price is expressed in units of the final good (numéraire).

¹⁴ Generally, the term 'physical capital' includes all **accumulated** or **produced** factors of production which are themselves output of some productive process.

Also, the same function abides to the known as *Inada conditions*

$$\lim_{L \rightarrow 0} \frac{\partial F(\bullet)}{\partial L} = \lim_{K \rightarrow 0} \frac{\partial F(\bullet)}{\partial K} = \infty \quad \text{and} \quad \lim_{L \rightarrow \infty} \frac{\partial F(\bullet)}{\partial L} = \lim_{K \rightarrow \infty} \frac{\partial F(\bullet)}{\partial K} = 0$$

Finally, it is $F(L, 0) = F(0, K) = 0$, meaning that production of positive output necessitates the use of positive amounts from both inputs.

The second fundamental equation of the neoclassical model is

$$\dot{K} = Y - cL - \delta K, \quad 0 < \delta < 1 \quad (21)$$

and describes how physical capital accumulates. The term on the left side of (21) is equivalent to the difference $K_{t+h} - K_t$ in *continuous time*, that is, when the interval between time periods $t + h$ and t is arbitrarily small (close to zero). Generalizing, a ‘dot’ over any variable (of time) such as K , stands for the first derivative of this variable with respect to time,

$$\dot{K} \equiv \lim_{h \rightarrow 0} \frac{K_{t+h} - K_t}{h} \equiv \frac{dK}{dt}, \quad h > 0$$

and measures the **net instantaneous change** of K in **absolute units**. The term $Y - cL$ on the right side of (21), is *total gross investment*. People spend on consumption a total amount equal to cL , where c is per capita consumption, whereas they save a value equal to $Y - cL$. The latter amount – total savings – is in turn invested in the production of new units of physical capital.¹⁵ Finally, the term δK measures the ‘wear and tear’ of physical capital during production. The assumption here is that a fixed proportion, δ , $0 < \delta < 1$, of the existing quantity of physical capital *depreciates* in every period. Evidently, the aggregate quantity of

¹⁵ Given that the economy is *closed*, total savings is equal to total investment.

physical capital, K , increases when $Y - cL > \delta K$, decreases if $Y - cL < \delta K$, and remains the same when $Y - cL = \delta K$.¹⁶

Application 1: Maximization of Per Capita Intertemporal Utility in the Standard Neoclassical Growth Model

In this section, the *Pareto optimal* steady state (dynamic long-run equilibrium) of the standard neoclassical growth model is presented. Optimality is ensured by the theoretical contrivance of an ideal *social planner* who is assumed to run the economy with objective to maximize the present value of the representative agent's total intertemporal utility.¹⁷ This will later permit us to better understand the possible growth-effect of enriching the neoclassical model with issues related to the environment.

The following equations (22)–(24) set the model as

$$Y = F(L, K) = L^\alpha K^{1-\alpha} \quad (22)$$

$$\dot{K} = L^\alpha K^{1-\alpha} - cL - \delta K \quad (23)$$

$$L_t = L_0 e^{nt} \Rightarrow \dot{L} = nL \Rightarrow \gamma_{\{L\}} = n \quad (24)$$

where $\gamma_{\{X\}} \equiv \frac{\dot{X}}{X}$ denotes the growth rate of any variable (of time) X . Equation (25)

poses the maximization problem

$$\max_c \int_{t=0}^{\infty} e^{-(\rho-n)t} U(c) dt = \max_c \int_{t=0}^{\infty} e^{-(\rho-n)t} \frac{c^{1-\sigma} - 1}{1-\sigma} dt \quad (25)$$

Equation (26) presents the current-value Hamiltonian

¹⁶ The last case describes a situation defined as the *steady state* of the model.

¹⁷ To achieve this, the planner takes all appropriate measures to counteract any existing *market failures*. Note that in the original neoclassical model there are no such failures. Hence, the results in this section are identical to the ones obtained in a market setting without any external intervention.

$$\mathcal{H} = \frac{c^{1-\sigma} - 1}{1-\sigma} + \mu_K (L^\alpha K^{1-\alpha} - cL - \delta K) \quad (26)$$

Equations (27)-(29) invoke the necessary conditions

$$\frac{\partial \mathcal{H}}{\partial c} = 0 \Rightarrow c^{-\sigma} = \mu_K L \quad (27)$$

$$\begin{aligned} \frac{\partial \mathcal{H}}{\partial K} = (\rho - n)\mu_K - \dot{\mu}_K &\Rightarrow \mu_K [L^\alpha (1-\alpha)K^{-\alpha} - \delta] = (\rho - n)\mu_K - \dot{\mu}_K \Rightarrow \\ &\Rightarrow \gamma_{\{\mu_K\}} = \rho - n + \delta - F_K(\bullet) \end{aligned} \quad (28)$$

$$\frac{\partial \mathcal{H}}{\partial \mu_K} = \dot{K} \Rightarrow \frac{\partial \mathcal{H}}{\partial \mu_K} = L^\alpha K^{1-\alpha} - cL - \delta K \quad (29)$$

Differentiation with respect to time of the logarithm of (27) yields

$$-\sigma \gamma_{\{c\}} = \gamma_{\{\mu_K\}} + n \quad (30)$$

Equating (28) and (30) results in

$$\gamma_{\{c\}} = \frac{F_K(\bullet) - \rho - \delta}{\sigma} \Rightarrow \gamma_{\{c\}} = \frac{L^\alpha (1-\alpha)K^{-\alpha} - \rho - \delta}{\sigma} \quad (31)$$

On the other hand it is known that

$$\gamma_{\{X\}} = \gamma_{\{x\}} + n \quad (32)$$

for $X = xL$, that is, aggregates grow at a rate higher by n in comparison to their respective per-capita magnitudes. Then, from (23) we may write

$$\gamma_{\{K\}} = \gamma_{\{k\}} + n = L^\alpha K^{-\alpha} - \frac{C}{K} - \delta \Rightarrow \frac{C}{K} = L^\alpha K^{-\alpha} - \delta - n - \gamma_{\{k\}} \quad (33)$$

But from (31) it is

$$K^{-\alpha} = \frac{\sigma \gamma_{\{c\}} + \rho + \delta}{(1-\alpha)L^\alpha} \quad (34)$$

Substitute for $K^{-\alpha}$ from (34) into (33) to obtain

$$\frac{C}{K} = \frac{\sigma\gamma_{\{c\}} + \rho + \delta}{1 - \alpha} - \delta - n - \gamma_{\{k\}} \quad (35)$$

which is constant as both $\gamma_{\{c\}}$ and $\gamma_{\{k\}}$ are constant by definition of steady state.

The fact that the ratio $\frac{C}{K} = \frac{Lc}{Lk} = \frac{c}{k}$ is constant implies

$$\gamma_{\{c\}} = \gamma_{\{k\}} \quad (36)$$

Further, since $\frac{K}{Y} = \frac{K/L}{Y/L} = \frac{k}{y}$ is constant, it is

$$\gamma_{\{y\}} = \gamma_{\{k\}} \quad (37)$$

Taking (36) and (37) into account we may write

$$\gamma_{\{y\}} = \gamma_{\{k\}} = \gamma_{\{c\}} \quad (38)$$

Now, note that $\gamma_{\{L\}} = n > 0$ and log-differentiate (34) to find

$$-\alpha\gamma_{\{K\}} = -\alpha\gamma_{\{L\}} \Rightarrow \gamma_{\{K\}} = n \quad (39)$$

But it is clear from (32) and (38) that

$$\gamma_{\{Y\}} = \gamma_{\{K\}} = \gamma_{\{C\}} \quad (40)$$

Then, combine equations (39) and (40) to show that in steady state this economy grows at a rate equal to the rate of growth of population

$$\gamma_{\{Y\}} = \gamma_{\{K\}} = \gamma_{\{C\}} = n \quad (41)$$

Finally, from equations (32), (38) and (41) we conclude that per-capita variables y , k and c display zero growth in steady state.

$$\gamma_{\{y\}} = \gamma_{\{k\}} = \gamma_{\{c\}} = 0 \quad (42)$$

Positive growth in per capita variables can be achieved in the neoclassical model by introducing technological progress. In this case the production function becomes

$$Y = F(AL, K) = (AL)^\alpha K^{1-\alpha}, \quad 0 < \alpha < 1 \quad (43)$$

where A is an index measuring the current level of technology.¹⁸

Observe that the *level of technology* as represented here by the *technological index* A , multiplies the available quantity of labor and results in *units of efficient labor*, L_e . In such a way technological progress increases labor productivity and makes it possible to produce larger quantities of output using the same aggregate amounts of labor L , and physical capital, K . Technological progress creates new productive knowledge at an exogenous rate g , that is,

$$A_t = A_0 e^{gt} \Rightarrow \dot{A} = gA \Rightarrow \gamma_{\{A\}} = g \quad (44)$$

where A_0 denotes the initial level of technology (period $t = 0$).

To account for technological change, we express variables in units of efficient labor L_e . This implies that the discount factor must now incorporate increases not only in population, but also in the quantity of efficient labor. We can easily see that the appropriate discount factor in the present case is $\rho - n - g > 0$, instead of $\rho - n > 0$ in the presence of population increases, and simply $\rho > 0$ in the original model. The impact of technological progress is clarified by working out the new optimization problem for the model expressed in units of efficient labor. This is achieved by dividing all aggregate variables (functions of time) by the quantity of efficient labor AL . Thus, we obtain the following: (subscripts denote ‘per unit of efficient of labor’.) Production per Unit of Efficient Labor

$$y_e = f(k_e) = k_e^{1-\alpha} \quad (45)$$

Accumulation of Physical Capital per Unit of Efficient Labor

¹⁸ This form of technological progress is known as *Harrod-neutral* or *labor-augmenting*.

$$\dot{k}_e = k_e^{1-\alpha} - c_e - (\delta + n + g)k_e \quad (46)$$

Maximization of Intertemporal Utility per Unit of Efficient Labor

$$\begin{aligned} \max_{c_e} \int_{t=0}^{\infty} e^{-\rho t} U(c_e) L_t A_t dt &= \max_{c_e} \int_{t=0}^{\infty} e^{-\rho t} U(c_e) L_0 e^{nt} A_0 e^{gt} dt \simeq \\ &\simeq \max_{c_e} \int_{t=0}^{\infty} e^{-(\rho-n-g)t} U(c_e) dt = \max_{c_e} \int_{t=0}^{\infty} e^{-(\rho-n-g)t} \frac{c_e^{1-\sigma} - 1}{1-\sigma} dt \end{aligned} \quad (47)$$

Current-Value-Hamiltonian

$$\mathcal{H} = \frac{c_e^{1-\sigma} - 1}{1-\sigma} + \mu_{k_e} (k_e^{1-\alpha} - c_e - \delta k_e - n k_e - g k_e) \quad (48)$$

Necessary Conditions

$$\frac{\partial \mathcal{H}}{\partial c_e} = 0 \Rightarrow c_e^{-\sigma} = \mu_{k_e} \quad (49)$$

$$\frac{\partial \mathcal{H}}{\partial k_e} = (\rho - n - g) \mu_{k_e} - \dot{\mu}_{k_e} \Rightarrow$$

$$\begin{aligned} \Rightarrow \mu_{k_e} [(1-\alpha)k_e^{-\alpha} - n - g - \delta] &= (\rho - n - g) \mu_{k_e} - \dot{\mu}_{k_e} \Rightarrow \\ &\Rightarrow \gamma_{\{\mu_{k_e}\}} = \rho + \delta - f'(k_e) \end{aligned} \quad (50)$$

where $f'(k_e) \equiv \frac{\partial f(k_e)}{\partial k_e}$.

$$\frac{\partial \mathcal{H}}{\partial \mu_{k_e}} = \dot{k}_e \Rightarrow \frac{\partial \mathcal{H}}{\partial \mu_{k_e}} = k_e^{1-\alpha} - c_e - n k_e - g k_e - \delta k_e \quad (51)$$

Going through the algebra as before, we find that all variables expressed in ‘per unit of efficient labor’ terms **do not** grow in steady state

$$\gamma_{\{y_e\}} = \gamma_{\{k_e\}} = \gamma_{\{c_e\}} = 0 \quad (52)$$

It is also known that

$$\mathcal{Y}_{\{x\}} = \mathcal{Y}_{\{x_e\}} + g \quad (53)$$

where $x = x_e A$. According to expression (53) per capita variables grow at a rate higher by g (the rate of technological progress) compared to the respective ‘per unit of efficient labor’ variables. Thus, relations (52) and (53) lead to

$$\mathcal{Y}_{\{y\}} = \mathcal{Y}_{\{k\}} = \mathcal{Y}_{\{c\}} = g \quad (54)$$

Finally, note that

$$\mathcal{Y}_{\{X\}} = \mathcal{Y}_{\{x\}} + n \quad (55)$$

where $X = xL$. Expression (55) states that aggregate variables grow at a rate higher by n in comparison to the respective per capita magnitudes (and at a rate higher by $n + g$ in comparison to the respective ‘per unit of efficient labor’ quantities.) Given expressions (54) and (55), we conclude that it is

$$\mathcal{Y}_{\{Y\}} = \mathcal{Y}_{\{K\}} = \mathcal{Y}_{\{C\}} = n + g \quad (56)$$

Application 2: Maximization of Per Capita Intertemporal Utility in the Neoclassical Growth Model with Pollution

In this section the *Environment* is introduced in the neoclassical growth model. It is assumed that environmental deterioration in the form of *Pollution* is created by, and associated with, the use of physical capital in production of the final good. No doubt, this has a negative impact on peoples’ welfare. At the same time, it is also assumed that pollution can be reduced by devoting part of aggregate output to *Abatement* activities. Specifically, it is assumed that ‘Pollution’, P_t , is a function of

the two variables just mentioned: the economy's aggregate stock of physical capital $K_t > 0$, and the level of 'Abatement' $B_t > 0$, both at time t .¹⁹

$$P_t \equiv P(K_t, B_t) = \left(\frac{K_t}{B_t} \right) \quad (57)$$

It is clear from equation (57) that the level of pollution is increasing with the aggregate quantity of physical capital and decreasing with expenditures (amount of resources used) on pollution abatement:

$$\frac{\partial P}{\partial K} \equiv P_K > 0 \quad \text{and} \quad \frac{\partial P}{\partial B} \equiv P_B < 0 \quad (58)$$

To ensure that the present model is consistent with a *steady state*, or *balanced growth path*, where all variables grow at **constant** – not necessarily equal – rates, the restriction is imposed that function $P(\bullet)$ is **homogeneous of degree 0 (zero)**.²⁰ In addition, per-capita consumption and the level of pollution enter the instantaneous utility function as *multiplicatively separable arguments* as in the following equation

$$U(c, P) = \frac{c^{1-\sigma} P^{-\vartheta(1-\sigma)} - 1}{1-\sigma}, \quad \sigma > 0, \quad \sigma \neq 1 \quad (59)$$

where $\vartheta > 0$ stands as a weight of pollution on utility.

Rewriting for convenience the model in aggregate terms one obtains the aggregate production function

$$Y = F(L, K) = L^\alpha K^{1-\alpha} \quad (60)$$

and the equation of physical capital accumulation

$$\dot{K} = L^\alpha K^{1-\alpha} - cL - \delta K - B \quad (61)$$

¹⁹ Note that all variables depend on time even though the time subscript is omitted whenever time dependence is easily understood.

²⁰ This guarantees a **constant level of pollution** in steady state.

Equation (61) also represents the economy's resource constraint asserting that total output, $Y = L^\alpha K^{1-\alpha}$, can be allocated into total consumption, $C = cL$, total gross investment in physical capital, $\dot{K} + \delta K$, and pollution abatement activities, B . Population again grows at a constant exogenous rate n

$$L_t = L_0 e^{nt} \Rightarrow \dot{L} = nL \Rightarrow \gamma_{\{L\}} = n \quad (62)$$

Dividing all aggregate variables by population we express the model in per capita terms as

$$y = f(k) = k^{1-\alpha} \quad (63)$$

$$\dot{k} = k^{1-\alpha} - c - (\delta + n)k - b \quad (64)$$

As regards the pollution level it is

$$P \equiv \frac{K}{B} = \frac{\frac{K}{L}}{\frac{B}{L}} = \frac{k}{b} \quad (65)$$

that is, total pollution is given by the constant ratio of physical capital to pollution abatement expenditures both in per-capita terms. Based on (65) the instantaneous utility function (59) becomes a function of per-capita consumption and per-capita expenditures on pollution abatement

$$U(c, P) \equiv U(c, b) = \frac{c^{1-\sigma} \left(\frac{k}{b} \right)^{-\mathcal{G}(1-\sigma)} - 1}{1-\sigma}, \quad \sigma > 0, \quad \sigma \neq 1 \quad (66)$$

Next, note that \mathcal{G} and $(1-\sigma)$ are constant and *logarithm, a monotonic function* of the original arguments in $U(\bullet)$, preserves utility orderings over a given set of

bundles of goods. Then, the instantaneous utility function (66) can equivalently be written as

$$W(c, P) \equiv \log U(c, P) = \log c - \mathcal{G} \log P$$

or, using (65)

$$W(c, P) \equiv W(c, k, b) = \log c - \mathcal{G} \log \left(\frac{k}{b} \right) \quad (67)$$

Similarly to the previous section, the optimization problem is

$$\max_{c, b} \int_{t=0}^{\infty} e^{-(\rho-n)t} \left[\log c - \mathcal{G} \log \left(\frac{k}{b} \right) \right] dt \quad (68)$$

and the respective current-value Hamiltonian becomes

$$\mathcal{H} = \log c - \mathcal{G} \log \left(\frac{k}{b} \right) + \mu_k [f(k) - c - (\delta + n)k - b] \quad (69)$$

Proceeding in the usual fashion, the necessary conditions

$$\frac{\partial \mathcal{H}}{\partial c} = 0 \quad (70)$$

$$\frac{\partial \mathcal{H}}{\partial b} = 0 \quad (71)$$

$$\frac{\partial \mathcal{H}}{\partial k} = (\rho - n) \mu_k - \dot{\mu}_k \quad (72)$$

along with $\dot{b} = 0$ and the standard steady-state conditions of the neoclassical model

$\dot{c} = \dot{k} = \dot{y} = 0$, yield

$$f'(k) = \rho + \delta + \frac{b}{k} \quad (73)$$

where $f'(k)$ is the marginal product of per-capita physical capital. It is now straightforward to compare with the steady-state condition of the original model (without environmental externalities) which is

$$f'(k) = \rho + \delta \quad (74)$$

Clearly, the marginal product of k in steady state is higher in the model that takes into account environmental effects.²¹ As a result, and due to the concavity of per-capita production $f(k) = k^{1-\alpha}$, condition (73) implies a steady state with smaller quantity of per-capita physical capital than (74). Thus, it is optimal for the economy to accumulate less physical capital than in the model without environmental effects. The reason is that physical capital is accompanied by the external (social) cost of pollution. This cost can be compensated in equilibrium by a higher marginal return of physical capital in production, which is possible only at a lower quantity of the said factor. As an end result, a lower level of per-capita output (income) is produced as fewer resources are put in the accumulation of physical capital while part of output is devoted to environmental protection. In terms of consumers' intertemporal utility one may suggest that, in a sense, what is lost because of lower per-capita consumption is returned thanks to improved environmental quality.

5. Empirical application

5.1 Data used

Using a sample of 43 countries with a full set of data for the variables of interest we explore the relationship between pollution in the form of carbon dioxide emissions, economic growth expressed by the gross domestic product and abatement approximated by the use of renewable energy sources in the production of electricity²² in the full sample of countries considered (n=43) as well as for the OECD (n=21) and non-OECD (n=22) countries for the time period 1990-2011.²³

²¹ Notice that the additional term in (73) is the (constant) ratio of per-capita abatement expenditures b , over per-capita physical capital k .

²² Another variable of interest for our purpose was the *greenhouse gases (GHG) net emissions/removals by LUCF* (in Mt of CO₂ equivalent) referring to changes in levels of all GHG

Specifically, carbon dioxide emissions per capita (CO_2/c in kt) stem from burning of fossil fuels and manufacture of cement and they comprise CO_2 produced throughout the consumption of solid, liquid, and gas fuels and gas flaring. Gross Domestic Product per capita GDP/c (in current US\$) is the sum of gross value added resident producers plus product taxes minus subsidies (not included in products' value). Deductions for depreciation of fabricated assets or degradation of natural resources are not considered.²⁴ Finally, renewable energy sources in the production of electricity (REN/c) represents electricity production per capita from renewable sources, excluding hydroelectric, including geothermal, solar, tides, wind, biomass, and biofuels.²⁵

5.2 Econometric methods

The basic specification of the model to be estimated may be expressed as:

$$Y_{it} = \beta_0 + X_{it}\beta_i + \alpha_i + \gamma_t + \varepsilon_{it} \quad (75)$$

where Y_{it} is the dependent variable and X_{it} is a k -vector of independent variables. Stochastic error terms are noted as ε_{it} for $i=1,2,\dots,M$ cross-sectional units in periods $t=1,2,\dots,T$. Parameters β_0 , α_i and γ_t correspond to the overall constant of the model and to cross-section and period specific effects (random or fixed) respectively. Countries are indexed by i and time by t .

The above equation has been estimated by various panel data methods. First the fixed effects (FE) method was applied permitting each country to have a different

attributable to forest and land-use change activities. Due to many missing values this variable was omitted from our analysis.

²³ The full sample database used has 946 observations per variable. The countries used are the following:

OECD countries (n=21): Australia, Austria, Canada, Chile, Denmark, Finland, France, Greece, Ireland, Italy, Japan, Korea, Luxembourg, Mexico, Netherlands, Norway, Portugal, Sweden, Turkey, UK, USA

Non-OECD countries (n=22): Argentina, Bolivia, Brazil, China, Colombia, Costa Rica, Caribbean, Cuba, Dominican Rep, Gabon, Guatemala, Indonesia, Nicaragua, Panama, Peru, Philippines, Senegal, Singapore, El Salvador, Thailand, Trinidad and Tobago, Uruguay.

²⁴ For more details see <http://data.worldbank.org/indicator/NY.GNP.PCAP.CD>

²⁵ The source of data is IEA Statistics © OECD/IEA 2012 (<http://www.iea.org/stats/index.asp>), subject to <https://www.iea.org/t&c/termsandconditions/>

intercept and treating α_i and γ_t as regression parameters. Then the random effects (RE) method was employed where individual effects are treated as random. That is α_i and γ_t are treated as components of the random disturbances. If country and time effects are correlated with the independent variables then RE model cannot be consistently estimated (Hsiao, 1986, Mundlak, 1978). Both FE and RE are inefficient in the presence of heteroskedasticity (Baltagi, 2001). To tackle heteroskedasticity and possible patterns of correlation in the residuals, Generalized Least Squares (GLS) specifications are used and the parameters estimation of GLS is given as:

$$\hat{\beta} = (X'\Phi^{-1}X)^{-1}X'\Phi^{-1}Y \quad (76)$$

Since the panel data employed in this study includes large N and T dimensions, non-stationarity should be explicitly considered and the dynamic misspecification of the pollutants' equations should be addressed, as pointed-out by Halkos (2003). If we base our analysis on a static model, then adjustments to any shock result in the same period in which these occur, but this could only be justified in equilibrium or if the adjustment process is fast. According to Perman and Stern (1999) this is unlikely to be the case and on the other hand, it is expected that the adjustment to long-run equilibrium emission levels is a particularly slow process.

An additional econometric concern for estimating the model is the potential bias occurring from the possible endogeneity between the renewable energy variable and CO₂/c emissions, since the use of renewables is expected to be greater in countries where air pollution is extensive.

To address the aforementioned concerns we employ the Arellano and Bond (1998) Generalized Method of Moments (A-B GMM). GMM controls for the endogeneity that is likely to exist in the determination of the dependent variables and alleviates potential reverse causality biases of the explanatory variables by employing

predetermined variables as instruments in a systematic way. Since there is evidence of heteroskedasticity we use the more relevant two-step Arellano–Bond procedure. Moreover, we report Orthogonal-Deviations GMM to control for fixed country effects.

To be more specific, we have used the GMM with its estimators relying on moments of the form

$$h(\beta) = \sum_{i=1}^N h_i(\beta) = \sum_{i=1}^N \Psi_i' u_i'(\beta) \quad (77)$$

With Ψ_i being a $T_i \times p$ matrix of instruments for cross section i and $u_i(\beta) = (Y_i - f(X_{it}, \beta))$. GMM minimizes the following quadratic form with respect to β

$$M(\beta) = \left(\sum_{i=1}^N \Psi_i' u_i(\beta) \right) W \left(\sum_{i=1}^N \Psi_i' u_i(\beta) \right) = \zeta(\beta)' W \zeta(\beta) \quad (78)$$

With W being a pxp weighting matrix. Orthogonal deviations state each observation in the form of deviations from the average of future sample observations and each deviation is weighted in such a way as to standardize variance (Arellano, 1988). That is:

$$x_{it}^* = \left[x_{it} - (x_{i(t+1)} + \dots + x_{iT}) / (T-t) \right] \sqrt{(T-t)} / \sqrt{T-t+1} \quad t=1, \dots, T-1 \quad (79)$$

The $(T_i - q)$ equations for unit i can be expressed as

$$Y_i = \delta w_i + d_i \eta_i + v_i \quad (80)$$

with δ being a parameter vector, w_i a data matrix with the time series of lagged endogenous variables, the x 's, and time dummies and d_i a $(T_i - q) \times 1$ vector of ones.

Linear GMM estimators of δ may be calculated as (Arellano and Bond, 1998)

$$\hat{\delta} = \left[\left(\sum_i w_i^*{}' Z_i \right) \frac{1}{\frac{1}{N} \sum_i Z_i' H_i Z_i} \left(\sum_i Z_i' w_i^* \right)^{-1} \left(\sum_i w_i^*{}' Z_i \right) \frac{1}{\frac{1}{N} \sum_i Z_i' H_i Z_i} \left(\sum_i Z_i' Y_t^* \right) \right] \quad (81)$$

where w_i^* and Y_i^* some transformation of w_i and Y_i like first differences and orthogonal deviations. Z_i and H_i are the instrumental variables and individual specific weighting matrices respectively.

Our initial model was a general dynamic model with the dependent and the independent variables lagged p and q times. Based on likelihood criteria (like the Akaike and Bayesian Information criteria) and omitting the insignificant dynamics we ended up to an autoregressive distributed lag model of AD(1,0). To specify how a country adjusts to the long-run equilibrium level of emissions a partial adjustment model was assumed of the form

$$\frac{(CO_2/c)_t}{(CO_2/c)_{t-1}} = \left(\frac{(CO_2/c)_t^*}{(CO_2/c)_{t-1}} \right)^\kappa \quad (82)$$

Where $(CO_2/c)_t$, $(CO_2/c)_{t-1}$ and $(CO_2/c)_t^*$ are the actual, the lagged by one period and the desired levels of emissions respectively and κ the adjustment coefficient ($0 < \kappa < 1$).²⁶

Box-Cox tests were used to establish the relationship to test linearity against logarithmic specification forms between the variables of interest and our tests indicate the following specification:

$$(CO_2/c)_{it} = \beta_0 + \alpha_i + \gamma_t + \beta_1(GDP/c)_{it} + \beta_2(GDP/c)_{it}^2 + \beta_3(GDP/c)_{it}^3 + \beta_4REN/c + \beta_5(CO_2/c)_{i,t-1} + \varepsilon_{it} \quad (83)$$

where CO_2/c is carbon dioxide emissions per capita, GDP/c is per capita Gross Domestic Product and REN/c the electricity production per capita from renewable sources.

Various tests and diagnostics are used. The Hausman test compares the slope parameters estimated by the fixed and random effects models considering the

²⁶ For more details see Halkos (2011).

inconsistency of the random effects model estimates. Rejection of the null hypothesis implies that the random effects model is inconsistently estimated and if there are no other econometric problems the fixed effects model should be used. Testing for cross-sectional dependence the Pesaran's (2004) cross-section dependence (CD) test is applied to estimate if the time series in the panel considered are cross-sectional independent.²⁷ The test is valid for large N and T in any order and is robust to structural breaks (Camarero et al., 2011). Moreover, a Breusch-Pagan LM test for individual effects for the random effects estimation robust standard errors is applied.

To examine the stochastic properties of the variables under consideration various unit root tests are usable (Levin, Lin and Chu, 2002; Harris and Tzavalis, 1999; Hadri, 2000; Breitung, 2000; Breitung and Das, 2005; Im, Pesaran and Shin, 2003;²⁸ and Fisher type²⁹ tests). The Levin–Lin–Chu, Harris and Tzavalis, and Breitung tests make the simplifying assumption that all panels share the same autoregressive parameter so that $\rho_i = \rho$ for all i ($\forall i$). The other tests however, allow the autoregressive parameter to be panel specific. Imposing the restriction that $\rho_i = \rho \forall i$ implies that the rate of convergence would be the same for all countries, an implication that is too restrictive in practice. On the other hand, the Im, Pesaran and Shin test allows for heterogeneous panels with serially uncorrelated errors but assumes that the number of time periods, T, is fixed. Fisher type tests allow for large T and finite or infinite N and are suitable in our case. Moreover, except for the Fisher tests, all the other tests require that there be no gaps in any panel's series.

Finally, panel co-integration tests are used. Pedroni (1999, 2000, 2004) proposed seven test statistics for the null of no co-integration; specifically, four panel

²⁷ STATA's "xtcsd" command was used (De Hoyos and Sarafidis, 2006).

²⁸ Im, Pesaran and Shin (2003) test is generally more powerful than the Fisher type and that proposed by Levin, Lin and Chu (2002) tests (Barbieri, 2006).

²⁹ Fisher type tests are based on combining the p-values of the N cross-sectional tests rather than using appropriately scaled cross-sectional averages of the N independent test statistics (Verbeek, 2005).

statistics and three group statistics testing either panel co-integration or cointegration across cross-sections.

5.3 Empirical results

Table 1 and Figure 1 present the descriptive statistics and the graphical presentation of the variables of interest respectively. Similarly, Table 2a presents some of the panel unit root tests for the variables under consideration. Graphical examinations indicate that both a trend and a constant term were to be included in the model formulation. The number of lags was determined using the Akaike and Schwarz information criteria. Looking at Table 2a we see support against non-stationarity in levels with our variables being I(1) implying that they are stationary in first differences and non-stationary in levels. Table 2b presents the Pedroni Cointegration tests where in four of the seven cases we reject the null hypothesis of no cointegration at the conventional statistical significance levels.

In the static model according to the Hausman test, FE is preferable to RE for the full sample, while RE estimates are preferable in the case of the non-OECD and OECD sub-samples. Based on the estimates of the static model, the extended use of renewable energy sources has a significantly negative direct effect on CO₂/c emissions. This effect is robust even after controlling for the income level and is consistent in all specifications examined.

Table 1: Descriptive Statistics of the variables considered

	Mean	Standard Deviation	Minimum	Maximum	No Obs
Full Sample					
CO ₂ /c	0.0064679	0.0061038	0.0003561	0.038338	946
GDP/c	16580.68	18348.33	243.9602	113731.7	
Renewables/c	179.2255	349.4798	0.0035237	2543.186	
OECD					
CO ₂ /c	0.010034	0.004903	0.002328	0.027431	462
GDP/c	30350.43	17960.97	2268.397	113731.7	
Renewables/c	385.857	538.4775	0.023097	2543.186	
Non-OECD					
CO ₂ /c	0.003397	0.005387	0.000356	0.038338	484
GDP/c	4624.17	6162.483	243.96	53122.25	
Renewables/c	51.759	71.1276	0.0035237	387.32	

Figure 1: Basic graphical presentation of the variables of interest

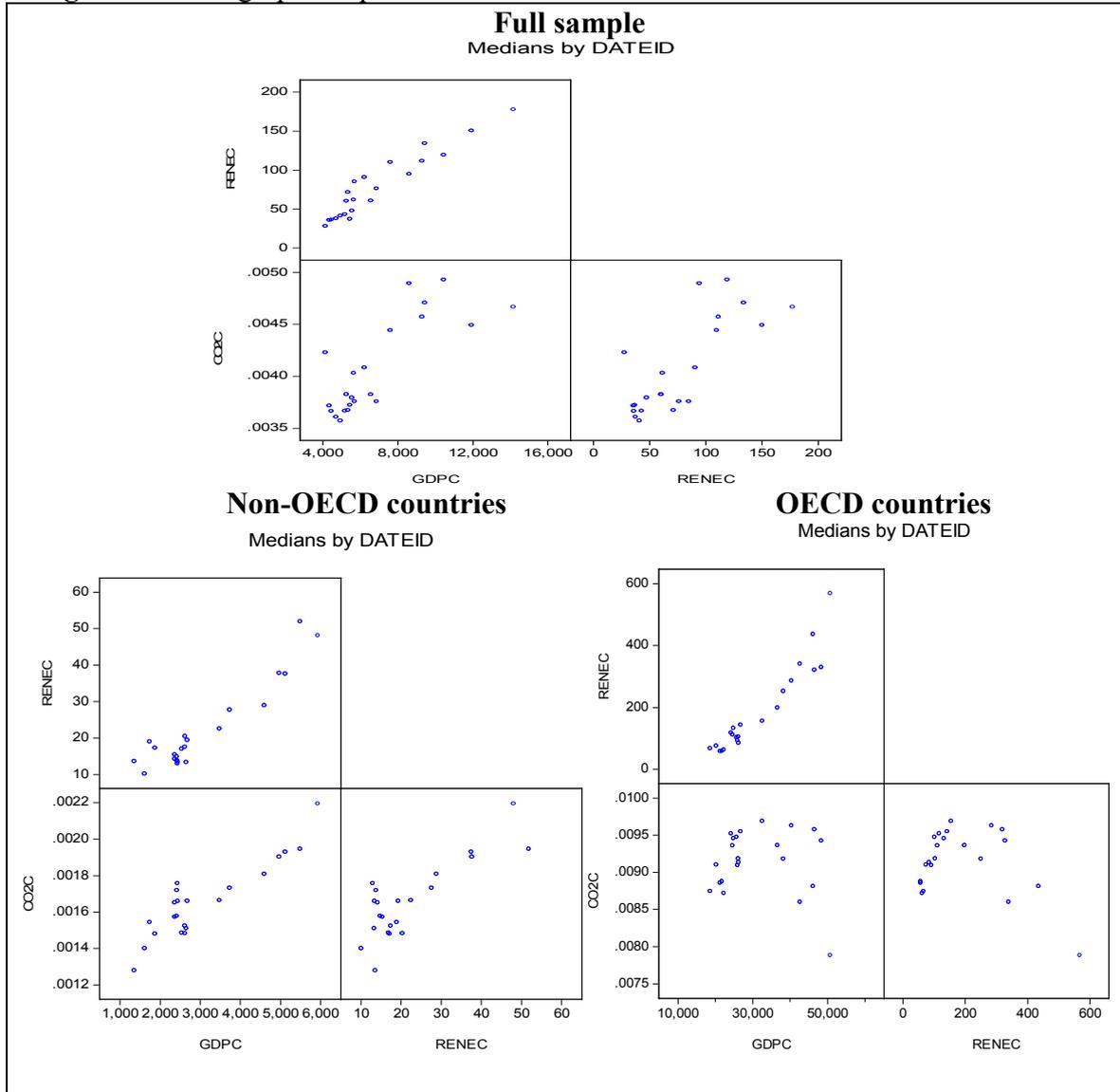


Table 2a: Summary of panel unit root tests (H_0 : Panels contain unit roots)

Levels	<i>Im, Pesaran, Shin W-stat</i>	<i>ADF- Fisher chi-square</i>	<i>PP- Fisher chi-square</i>	First Differences	<i>Im, Pesaran, Shin W-stat</i>	<i>ADF- Fisher chi-square</i>	<i>PP- Fisher chi-square</i>
CO ₂ /c	0.9091	0.1129	0.4705	ΔCO ₂ /c	0.0000	0.0000	0.0000
	0.9828	0.1274	0.4599		0.0000	0.0000	0.0000
	0.9837	0.8586	0.4189		0.0000	0.0000	0.0000
GDP/c	1.0000	0.9986	1.0000	ΔGDP/c	0.0000	0.0000	0.0000
	0.4397	0.6798	0.9999		0.0000	0.0000	0.0000
	1.0000	1.0000	1.0000		0.0007	0.0007	0.0000
GDP/c ²	1.0000	0.9835	1.0000	ΔGDP/c ²	0.0000	0.0000	0.0000
	0.3058	0.1345	1.0000		0.0000	0.0000	0.0000
	1.0000	1.0000	1.0000		0.0745	0.0002	0.0000
GDP/c ³	1.0000	0.2734	1.0000	ΔGDP/c ³	0.0000	0.0000	0.0000
	0.0005	0.0005	1.0000		0.0000	0.0000	0.0000
	1.0000	1.0000	1.0000		0.7658	0.0000	0.0000
RENEW/c	1.0000	0.3272	0.8191	Δ(RENE/c)	0.0000	0.0000	0.0000
	1.0000	0.9879	0.9999		0.0002	0.0000	0.0000
	1.0000	0.8423	0.0655		0.0012	0.0000	0.0000

All values reported are probabilities and refer to the Full, OECD and non-OECD samples, respectively.

Table 2b: Pedroni cointegration test (H_0 : No cointegration) (deterministic intercept and trend)

	Full Sample		OECD		Non-OECD	
	Statistic	Prob.	Statistic	Prob.	Statistic	Prob.
Panel v-Statistic	-2.977	0.9985	-1.7259	0.9578	-2.6866	0.9964
Panel rho-Statistic	4.2202	1.0000	0.8700	0.8079	2.8990	0.9981
Panel PP-Statistic	-7.2062	0.0000	-2.1099	0.0174	-10.1054	0.0000
Panel ADF-Statistic	-5.2513	0.0000	-3.3589	0.0004	-9.3234	0.0000
Group rho-Statistic	4.8523	1.0000	0.9291	0.8236	3.6634	0.9999
Group PP-Statistic	-12.698	0.0000	-4.4934	0.0000	-11.0153	0.0000
Group ADF-Statistic	-2.5008	0.0062	-5.4000	0.0000	-3.3430	0.0004

To tackle the various concerns mentioned in the previous sub-section we use the A-B GMM. The significance of the lagged dependent variable (p-value = 0.000) suggests that dynamic specifications should be preferred.³⁰ It should be noted that the assumption of uncorrelated errors is important here, so tests for first- and second-order serial correlation related to the residuals from the estimated equation are reported in the last columns. These tests are asymptotically-distributed as normal variables under the null hypothesis of no-serial correlation. The test for AR(1) is rejected as expected, while there is no evidence that the assumption of serially uncorrelated errors is inappropriate in all significance levels. For all specifications we test the validity of instruments with the Hansen test, which failed to reject the null that the instrumental variables are uncorrelated with the residuals. The reported J-statistic is related to the Sargan statistic and the value of the GMM objective function at the estimated parameters while the Wald χ^2 test strongly rejects the null hypothesis (of all coefficients being zero).

Columns 4-6 in Table 3 report GMM Orthogonal-Deviations estimates of the pollution equation. Taking into account endogeneity in the A-B GMM estimates the effect of renewable energy sources on CO₂/c emissions remains significantly negative

³⁰ As mentioned before, our dynamic model specification was reduced to an autoregressive distributed lag model [AD(1,0)], which for simplicity is called dynamic.

in all cases considered.³¹ The rate of adjustment that emissions adjust to their equilibrium values is very slow. The lag coefficients in the estimated models show that the adjustment of emissions (to the assimilative capacity of the environment) proceeds at a rate of 9% (1-0.91) in the cases of the full sample and the non-OECD countries and at a rate of 22% (1-0.78) in the case of OECD countries. That is 9% (full sample and non-OECD) and 22% (OECD countries) of the discrepancies between the desired and the actual emissions levels are adjusted each year requiring approximately almost 11 and about 5 years respectively for adjustment. The causes of these slow adjustments should be sought mainly in the characteristics of pollutants (Global Warming Potential³², etc) but also in the institutional and firms/industries characteristics of industrial markets in the countries considered as well as in the fuels used under the current regulations.

The turning points are within the samples. They start at the level of \$24839 (non-OECD countries) and reach the level of \$80584 (full sample) in the static specification. On the other hand, in the dynamic specification the turning points start at higher levels of \$32288 and reaching the level of \$96393 in the case of the full sample. We have support of the EKC hypothesis in the case of non-OECD countries both in the static and dynamic analyses and in the OECD countries in the dynamic analysis. We have ended up with N-shape curves in the case of the full sample in both static and dynamic specification and in the OECD countries in the static specification.

Finally, Figure 2 closely associated with the results of Table 3 shows the graphical presentations of the variables CO₂/c and GDP/c after the consideration of electricity production using renewable energy sources in both static and dynamic

³¹ The long-run coefficients of the GMM estimates may be calculated by dividing each estimated short-run coefficient by one minus the coefficient of the lagged dependent variable.

³² For more information on Global Warming Potential, the dimensions of the problem of climate change and its economic effects see Halkos (2014, 2015).

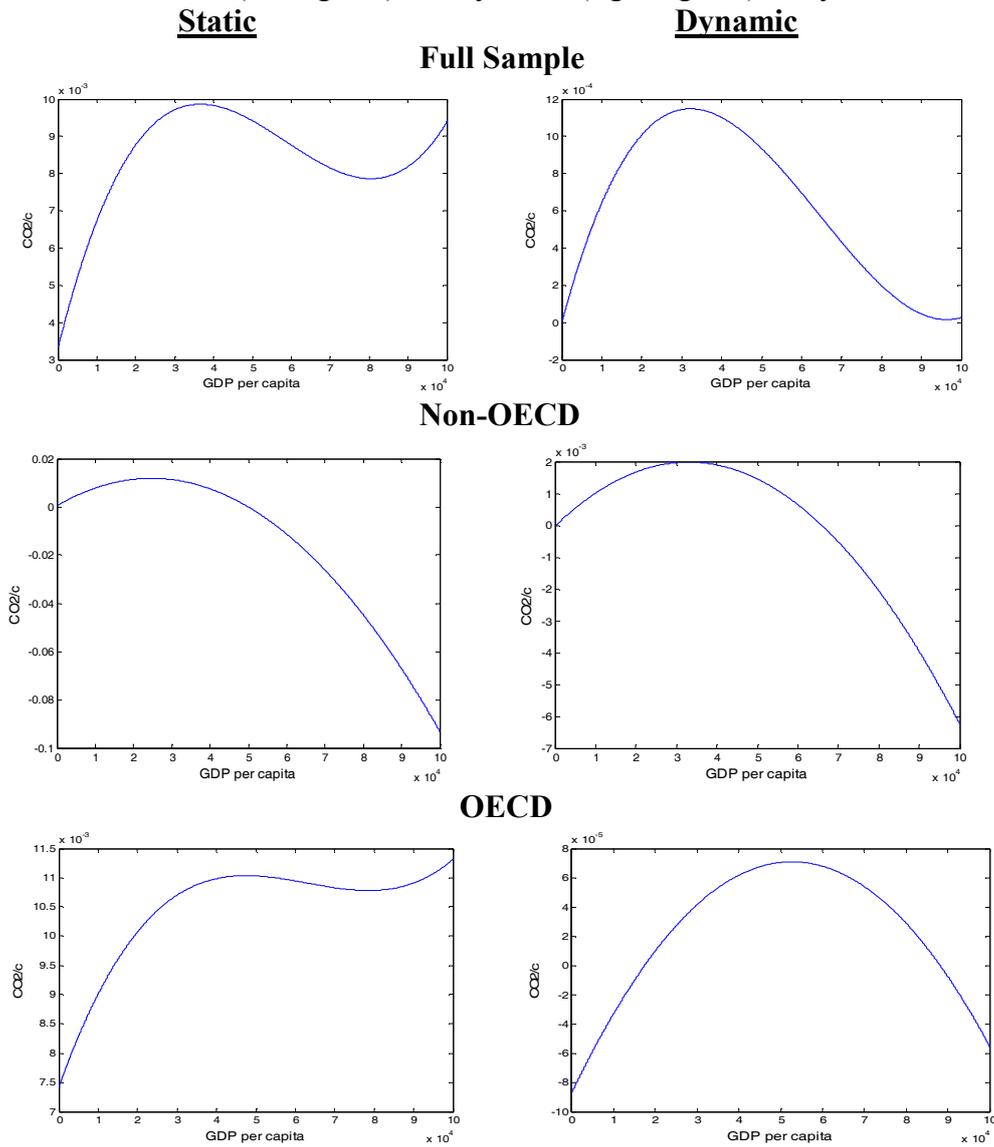
analyses. There are significant differences when dynamic specifications are considered. These differences are more obvious in the case of total and OECD countries samples.

Table 3: Econometric Results

Model	Full sample Fixed effects with Driscoll- Kraay s.e.	Non-OECD Random effects GLS	OECD Random effects GLS	Full sample GMM Orthogonal Deviations Two-Step	Non-OECD GMM Orthogonal Deviations Two-Step	OECD GMM Orthogonal Deviations Two-Step
Constant	0.00329 [0.0000]	0.000795 [0.3770]	0.007616 [0.0000]			
GDP/c	4.22e-07 [0.0000]	9.24e-07 [0.0000]	1.91e-07 [0.0000]	8.03e-08 [0.0000]	1.22e-07 [0.0000]	5.99e-09 [0.0150]
GDP/c ²	-8.36e-12 [0.0000]	-1.86e-11 [0.0000]	-3.22e-12 [0.0000]	-1.66e-12 [0.0000]	-1.84e-12 [0.0000]	-5.67e-14 [0.0020]
GDP/c ³	4.75e-17 [0.0007]		1.70e-17 [0.0000]	8.60e-18 [0.0000]		
Renewable/c	-1.18e-06 [0.0000]	-0.000019 [0.0000]	-1.24e-06 [0.0000]	-5.42e-08 [0.0000]	-1.58e-06 [0.0000]	-5.15e-07 [0.0000]
(CO ₂ /c) _{t-1}				0.908306 [0.0000]	0.908022 [0.0000]	0.78065 [0.0000]
Turning Points	36749 & 80584	24839	47606 & 78668	32288 & 96393	33152	52910
R ²	0.53	0.421	0.233			
Pesaran's test of cross-sectional interdependence	17.78 [0.0000]	10.499 [0.0000]	10.848 [0.0000]			
Hausman Test	10.71 [0.0047]	1.38 [0.5025]	4.57 [0.1083]			
Breusch-Pagan cross-sectional dependence	6682.32 [0.0000]	3604.61 [0.0000]	3259.91 [0.0000]			
A-B Test AR(1)				-3.03	-3.02 [-2.64 [
A-B Test AR(2)				-1.04	-1.07	-0.36
Hansen Test				-7.54 [1.0000]	18.85 [1.0000]	16.71 [1.0000]
J statistic				19.085 [0.4299]	19.345 [0.4349]	17.55076 [0.35085]
Wald χ^2 test				83232 [0.0000]	138000 [0.0000]	85169 [0.0000]
Observations	946	484	462	860	440	420

Figures in brackets are P-values. Tests of significance are based on robust standard errors in each case. The two-step GMM standard errors are Windmeijer's finite sample corrected.

Figure 2: CO₂/c versus economic growth after considering renewable/c in static (left figures) and dynamic (right figures) analyses



6. Conclusions and policy implications

In this study with the use of a balanced panel data of 43 countries and for the time period 1990-2011 we have tested the validity of including the environment in the neoclassical growth model for the full sample, as well as for the OECD and non-OECD countries. We have used CO₂/c emissions as a proxy for pollution, GDP/c as representing economic growth and electricity production per capita from renewable sources as approximation for pollution abatement. In our model specification and in

both static and dynamic analyses the variables were statistically significant. The use of renewable energy as a proxy for abatement was (as expected) negatively associated with CO₂ emissions although with a low magnitude.

Having also considered dynamic formulations, the significance of the lagged dependent variable implied a preference for dynamic specifications. Specifically, CO₂ lagged by one period is positive and statistically significant in all cases indicating that high carbon dioxide emissions do take place continuously as we move through time possibly due to the costs imposed in abating emissions. Actually, the rate of emissions adjustment to equilibrium values was really slow proceeding at rates of 9% in the cases of the full sample and the non-OECD countries and 22% in the case of OECD countries.

The turning points estimated were within the samples starting at a level of \$24839 for non-OECD countries in a static specification and reaching a level of 96393 in the case of the full sample and in a dynamic formulation. We have found support of the EKC hypothesis in the case of non-OECD countries both in the static and dynamic analysis and in the OECD countries in the dynamic analysis and an N-shape curve for the full sample in static and dynamic models and for OECD countries in static specification.

There are various reasons justifying the existence of the EKC hypothesis. Among them we may have the progress in environmental quality that stems from the technological progress (de Bruyn, 1997; Han and Chatterjee, 1997), the technological link between consumption of desired goods and abatement of the associated undesirable by-products like pollution or environmental damage (Andreoni and Levinson, 2001) and pollution will stop increasing and start to decrease with economic growth due to various constraints becoming non-binding (Lieb, 2003).

The expected evolution of economic development naturally starts from clean agricultural production and moves on to more polluting industrial activities ending up to cleaner service economies. In this way we face *scale*, *composition* and *technical* effects (Grossman and Krueger, 1995; Dinda, 2004; Everett *et al.*, 2010; Halkos, 2012). Similarly, preferences and emissions' regulations are important. Better governance together with credible property rights and regulations are able to lead to public awareness and as a result to reduction in environmental damage (Lopez, 1994; McConnell, 1997; Stokey, 1998). Dinda *et al.* (2000) propose that technological progress, structural changes and higher R&D and per capital income levels are important in setting up the nature of the relationship between growth and environment.

Besides our task in this paper, it is worth mentioning that the economic effects of climate change have been widely discussed and are in the Stern Review (2007) concluding that the no-action costs would be approximately equal to 5% of global GDP yearly compared to almost 1% if actions are taken. Obviously, energy availability and independence may be drivers of economic growth while dependence on fossil fuels could be an obstacle for the sustainable development of countries. Renewable energy sources may be a way out of this dependence on fossil fuels and help in decreasing the amount of greenhouse gases coping in this way with the climate change problem.

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