

Marginal Costs of Carbon Dioxide Abatement: Empirical Evidence from Cross-Country Analysis

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1. Introduction

A recent trend of research examines the existence of an inverted U-shaped relationship, called the Environmental Kuznets Curve (EKC), between environmental quality and national income per capita (GROSSMAN and KRUEGER, 1993; SHAFIK and BANDYOPADYAY, 1992). If this inverse-U pattern exists, some authors argue that economic development by itself is a panacea for environmental degradation.¹ However, the question of when the EKC may appear and by which economic factors and mechanisms it might be explained remains poorly understood.

The emergence of the EKC is usually explained by the evolution of the demand for and supply of environmental quality occurring in the course of economic growth. On the demand side, at different stages of economic development people are typically characterised by different willingness to pay for the cleaner environment. On the supply side, the possibilities to abate pollution – which depend on pollution abatement costs – are influenced among others by the current state of technology. Obviously, the latter depends on the degree of economic

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¹ Recent surveys and meta-analysis of the available empirical evidence show that this inverted U-shaped pattern is not stable across countries, types of pollutants, data sources and econometric methods (EKINS, 1997; CAVLOVIC, BAKER, BERRENS and GAWANDE, 2000; LIEB, 2003).

development. Therefore, both factors – the willingness to pay for the cleaner environment, and the importance of pollution abatement costs – influence the relationship between the economic affluence and the amount of pollution emissions (i.e., the EKC).

The purpose of this paper is to advance an evidence-based approach to understand the impact of income growth on the marginal cost of pollution abatement. The cost of abatement is defined as the forgone production of desirable output resulting from the reallocation of inputs to pollution abatement activities. The marginal opportunity cost of abatement is the cost of getting rid of the “last” unit of pollutant. Concentrating on the emissions of carbon dioxide (CO₂) in several developing and developed countries, this paper addresses the following questions: what are the countries where the abatement of carbon dioxide is the least/most expensive?; which economies dispose of zero-cost CO₂ reduction opportunities?; and why the empirical evidence regarding the existence of the EKC for CO₂ emissions is so controversial? To answer these questions, the relationship between the marginal abatement costs of CO₂ emissions and the GDP per capita is empirically estimated.

Until now, important empirical research investigated the existence of the EKC itself for different countries and pollutants. Some studies analysed the attitude towards environmental protection (INGLEHART, 1995) and the evolution of the willingness to pay for the cleaner environment (MCCONNEL, 1997; KRISTRÖM and RIERA, 1996). Estimations of pollution abatement costs were rare. BLUFFSTONE (1997), HARTMAN, SINGH and WHEELER (1994), and DASGUPTA, HUQ, WHEELER and ZHANG (1996) have examined abatement costs for air and water pollutants. These estimates were limited to the case studies of one, or few, economies, and were not directly comparable across countries. Our results allow for a comparison of CO₂ abatement costs across a large number of economies, and they constitute an attempt to build a bridge between the literature estimating pollution abatement costs and the studies explaining the emergence of the EKC.

Recent developments in the production theory allow us to model the joint production of desirable outputs (GDP or consumption) and undesirable by-products (pollution), and to infer the shadow prices of pollutants equal to marginal opportunity costs of abatement (FÄRE and GROSSKOPF, 1998). The analysis is performed through estimation of a non-parametric production frontier for a cross-section data set of 76 developed and developing countries observed in the year 1985. The results provide evidence of a decreasing marginal opportunity cost of CO₂ abatement as national income grows. Developed countries are less penalised by immediate pollution reductions, in terms of the GDP or consumption forgone, than the developing ones. The quantities of carbon emissions that

could be potentially avoided by inefficient countries at zero opportunity cost are also assessed. They are unrelated to the degree of economic affluence. Finally, interpretations useful for both policy making and theoretical and empirical EKC research are made available.

The focus on CO₂ emissions is interesting for at least two reasons. First, empirical evidences regarding the existence of the EKC for the CO₂ emissions are mixed.² Therefore, deeper investigations of the reasons for the emergence of the EKC are useful. Second, as carbon dioxide – a greenhouse gas (GHG) – is a global public bad, the largest abatement should be undertaken in countries where abatement costs are the lowest. International emissions trading mechanisms embedded in the Kyoto Protocol rely on this argument.

The layout of this paper is as follows. Section 2 briefly reviews theoretical literature on the EKC. It emphasises the importance of the evolution of abatement costs as income grows in order to explain the emergence of the EKC. Section 3 explains the procedure of estimation of marginal abatement costs. Sections 4 and 5 present data and results. Section 6 interprets the findings in the light of economic theory summarised in Section 2, and the last section concludes.

2. Environmental Kuznets Curve and Opportunity Costs of Pollution Abatement

2.1. Theoretical Arguments Underlying the EKC

Theoretical models giving rise to the EKC focus on hypothesis concerning the demand for and the supply of environmental quality. On the demand for environmental quality side, it is generally assumed that pollution causes disutility, so that there is willingness to pay for emission abatement. According to BECKERMAN (1992) and CHAUDHURI and PFAFF (2002), this demand increases with income, resulting in positive income elasticity for environmental quality.³ As the development proceeds, people place a higher value on immaterial goods, so that they are induced to develop higher willingness to pay for, or to accept the opportunity cost

2 Majority of studies report a rising relation between pollution and income (AGRAS and CHAPMAN, 1999; LIM, 1997; SHAFIK and BANDYOPADHYAY, 1992; BORGHESI, 2000; PERRINGS and ANSUATEGI, 2000). However, DIJKGRAAF and VOLLEBERGH (1998) and CARSON, JEON and McCUBBIN (1997) find an inverted U-shaped curve.

3 ANSUATEGUI, BARBIER and PERRINGS (1998), NEUMAYER (1998), COLE (2000), and DE BRUYN (2000) argue that environmental quality is a luxury good.

of, environmental protection. VOGEL (1999) and PANAYOTOU (1997) note that a high level of environmental awareness is likely to arise in developed countries due to visible and large environmental damages caused by pollution. Moreover, economic growth is often accompanied by the development of effective institutions for collective decision-making. These institutions are able to properly internalise negative environmental externalities (JONES and MANUELLI, 1995), or to facilitate the replacement of dirty technologies by cleaner ones (STOKEY, 1998). Therefore, governments are likely to impose increasingly strict pollution control policies, as their citizens' income increases.

On the supply of environmental quality side, pollution abatement costs depend on technology and production-consumption mix and therefore, vary throughout the stages of economic growth. Accordingly, assumptions regarding returns to scale in pollution abatement are often part of theoretical models.⁴ The EKC may also be due to the structural change that accompanied economic development. During the last 150 years, the developed countries experienced a transition from clean agrarian to polluting industrial, and then to clean service economies (ARROW, BROLIN, COSTANZA, DASGUPTA, FOLKE, HOLLING, JANSSON, LEVIN, MÄLER, PERRINGS and PIMENTEL, 1995). HETTIGE, MANI and WHEELER (1992) and SURI and CHAPMAN (1998) further argue that transition to clean service economies (composition effect) is reinforced by the displacement of pollution-intensive activities from developed to developing countries. They explain this process by the existence of tighter environmental regulations in the developed economies as compared to the developing ones (pollution heaven hypothesis). Finally, some authors emphasise that pollution abatement starts only when a threshold in the economic activity is attained. STOKEY (1998) assumes that below a threshold level of activity, only the dirtiest technology can be used, but when the threshold is passed, cleaner technologies become available.

2.2. Review of Some Theoretical Models

Several models giving rise to the EKC are derived from the theoretical arguments presented above. We shortly review some models taking into account pollution abatement opportunities and costs. MUNASINGHE (1999) considers a series of equilibriums resulting from interactions between demand and supply of

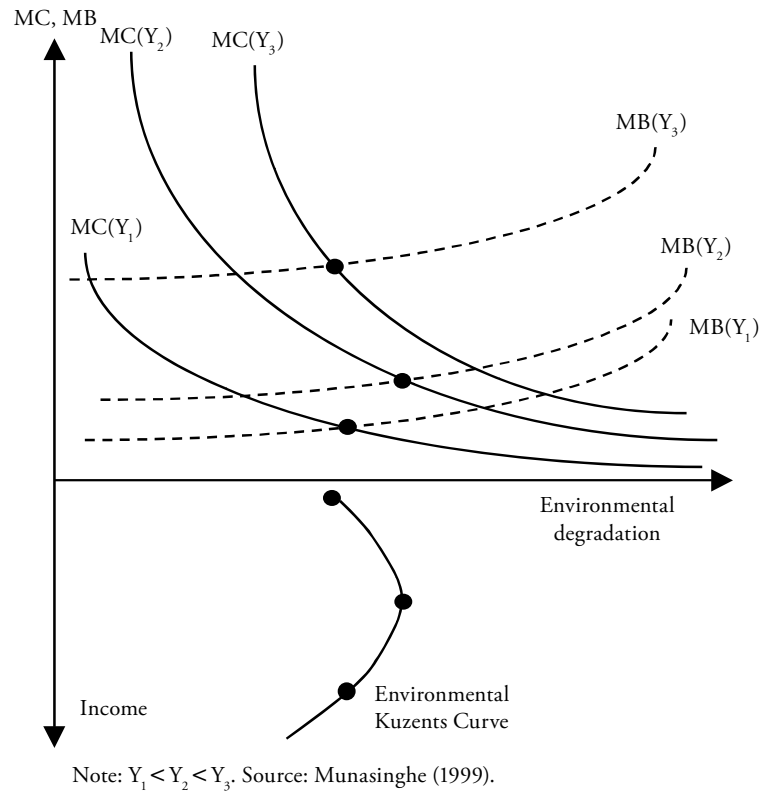
4 Constant (increasing, decreasing) returns to scale in pollution abatement process prevail if $\partial P / \partial E < 0$ and $\partial^2 P / \partial E^2 = (<, >) 0$, where P and E denote pollution and expenditure on abatement, respectively.

environmental quality, and shows how these interactions can lead to the emergence of EKC. The analysis is based on standard theoretical framework that may be summarised by means of the marginal benefit (MB) and the marginal abatement cost (MC) curves (BAUMOL and OATES, 1988). The MB curve represents the marginal social benefit of emission reduction as a function of environmental degradation. It has a positive slope, indicating that the greater the degree of environmental degradation that has already been attained, the larger the marginal benefit of the existing environmental quality. Similarly, MC, the marginal pollution abatement cost curve is decreasing because of the rising cost of further abatement, as the zero environmental degradation point is approached. The optimal point of environmental degradation is given by the intersection of the MC and MB curves, where the marginal cost and benefit of pollution abatement are equal.

Extending this framework by assuming that income level may affect MC and MB curves, MUNASINGHE (1999) shows that the EKC arises under condition that when income grows, the MC and MB curves shift upwards, MC at a decreasing pace, MB at an increasing one. Figure 1 shows that the EKC emerges if the MC curve shifts upward more than the MB curve at low levels of income. The assumption of the upward shift of the MB curve when income grows is driven by the hypothesis of positive income elasticity of the demand for environmental quality. The hypothesis that the MC curve shifts upward when the income grows has not yet been tested empirically. This paper proposes to test this latter for the CO₂ emissions.

Alternative models of theoretical micro-foundations of the EKC taking into account abatement costs are proposed by VOGEL (1999), SELDEN and SONG (1995) and ANDREONI and LEVINSON (2001), among others. VOGEL (1999) shows that increasing willingness to pay for environmental quality as income grows, combined with constant returns to scale in pollution abatement represent sufficient conditions to ensure that environmental quality improves with rising income per capita. However, this result does not hold anymore if the costs of abatement increase throughout economic growth. Accordingly, SELDEN and SONG (1995) show that the extent to which increasing abatement costs offset the demand effect associated with rising income depends of the pace of capital growth and the impact of that growth on pollution. They also suppose that emission reduction is carried out only once the development has created enough wealth and environmental damage to merit abatement. Finally, ANDREONI and LEVINSON (2001) show that the emergence of the EKC may be explained by using a standard microeconomic approach, where pollution is a by-product of consumption. Pollution causes disutility, so that consumers may devote their income either

Figure 1: Deriving the Environmental Kuznets Curve



to consumption or to pollution abatement. If the economy is characterised by increasing returns to scale in pollution abatement process (implying that a larger producer faces lower abatement costs), then the EKC arises endogenously. The authors justify the hypothesis of increasing returns to scale by arguing that pollution abatement technologies are characterised by high fixed and low marginal costs. They also present empirical evidences of increasing returns to scale existing in the pollution abatement in the U.S. industries. The model is quite general, so that neither technological progress, nor a change in preferences or in the regulatory framework is necessary for the EKC to arise.

To sum up, the inverse-U curve is usually explained by the evolution of the demand for and supply of environmental quality occurring in the course of

economic growth. While the demand of environmental quality was quite often analysed, its supply deserved little attention. However, variations in abatement costs intervene in determining the pollution-income path. Abatement costs are likely to vary across countries and levels of income. The structural economic changes occurring throughout economic growth and technological developments may explain these differences. The development of environmental institutions may lead high-income economies towards the usage of better and cheaper environmental strategies. On the other hand, stricter regulation and the reduction of the carrying capacity of the environment as development proceeds may necessitate ever-greater abatement effort to offset the direct effects of growth on the environmental degradation (SELDEN and SONG, 1995). As one theoretical effect may counter-balance the other, an empirical study is necessary.

Empirical evidences regarding the variations of abatement costs across different levels of income or between countries are rare. Intergovernmental Panel on Climate Change (IPCC, 2001) reviews national studies on CO₂ abatement costs and argues that these costs are generally lower in the less developed economies than in more developed ones. However, IPCC's conclusions are based more on theoretical models than on empirical studies (CHAPMAN and KHANNA, 2000), pertain to *future* cost projections, and do not offer results on the opportunity cost, or amount of GDP loss, resulting from abatement. Abatement costs for air pollutants have been empirically examined by BLUFFSTONE (1997) for Lithuania and HARTMAN, SINGH and WHEELER (1994) for the USA. DASGUPTA, HUQ, WHEELER and ZHANG (1996) estimate marginal costs of reducing water pollutants in China. Other available case studies estimate the abatement costs associated to introduction of a particular legislation, or concentrate on a particular plant or industrial sector (PIZER and KOPP, 2003). To the best of our knowledge, there exists no comparison of pollution abatement costs across a large number of economies; neither abatement costs of carbon dioxide have drawn much attention.

3. Estimating the Shadow Prices of Undesirable Outputs

In order to analyse evolution of the opportunity costs of CO₂ abatement with income, this paper reports empirical evidence based on a production model. Technology is modelled by means of directional output distance function, which allows to determine the amount of desirable output that a country should forgo in order to get rid off the last "unit" of pollution emitted. We also identify economies characterised by potential zero-cost CO₂ abatement opportunities.

This section describes the theoretical modelling of production process characterised by the joint production of desirable and undesirable outputs. We assume that the units under investigation – which are the countries in our case⁵ – employ multiple inputs denoted by a vector $x = (x_1, x_2, \dots, x_p) \in \mathfrak{R}_+^p$ to produce a vector of desirable outputs (goods, e.g., GDP or consumption) $y = (y_1, y_2, \dots, y_Q) \in \mathfrak{R}_+^Q$ and a vector of undesirable outputs (bads, or pollution emissions) $b = (b_1, b_2, \dots, b_R) \in \mathfrak{R}_+^R$. The technology may be described in a very general way via the output correspondence (or requirement) set (FÄRE and LOVELL, 1985):

$$Y(x) = \{(y, b) \mid x \text{ can produce } (y, b)\}. \quad (1)$$

Following CHUNG, FÄRE and GROSSKOPF (1997), we impose standard assumptions on $Y(x)$: it is a closed, bounded, convex set with inputs and desirable outputs that are freely disposable, undesirable outputs weakly disposable, and desirable and undesirable outputs null-joint.⁶ Figure 1 depicts an example of production set $Y(x)$ that satisfies these assumptions. Note that for each vector $(y, b) \in Y(x)$, proportional contractions of any feasible output are feasible. Also, the good output is freely disposable. Finally, the good and bad outputs are null-joint: if $b = 0$, then $y = 0$ whenever (y, b) is in $Y(x)$.

The main analytical tool we employ is the directional output distance function introduced by CHUNG, FÄRE and GROSSKOPF (1997) and CHAMBERS, CHUNG and FÄRE (1998). This function is the output version of LUENBERGER'S (1992) benefit function and it inherits the properties imposed on the output set $Y(x)$. It was employed to compute shadow prices of undesirable outputs by LEE, PARK and KIM (2002). Denote the directional output vector by $g = (g_b, g_y)$, where $g_b = (g_{b1}, g_{b2}, \dots, g_{bR}) \in \mathfrak{R}_-^R$ and $g_y = (g_{y1}, g_{y2}, \dots, g_{yQ}) \in \mathfrak{R}_+^Q$. The associated directional output distance function is defined as:

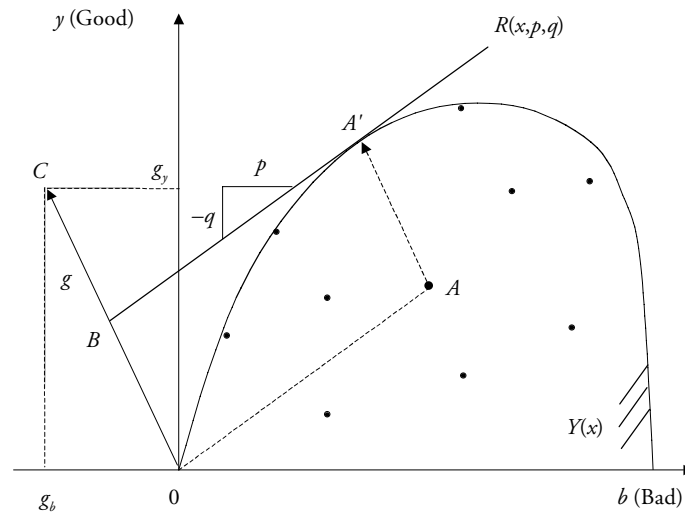
$$D_o(x, y, b; g) = \sup\{\beta \mid (y, b) + \beta g \in Y(x)\}. \quad (2)$$

The directional distance function scales good and bad outputs in a chosen direction, g , to the frontier of output correspondence set $Y(x)$. Since $g_b \leq 0$ and $g_y \geq 0$, bad outputs are decreased and good outputs are increased. The function says how

5 This section refers to activity analysis, which is often used to model the production process of individual firms. It was also employed (e.g., by FÄRE, GROSSKOPF, NORRIS and ZHANG, 1994) to construct the production frontier for a sample of countries.

6 For more details on these assumptions, see Appendix 1.

Figure 2: Output Correspondence Set $Y(x)$ and Directional Output Distance Function for a Given Input Mix



Notes: $OA \parallel BA'$, $OB \parallel AA'$. For country A , $D_0^A(x, y, b; g) = \beta = OB/OC$.

for (y, b) must be projected along g to reach the frontier of production set. Directional distance function takes the value of 0 if the unit is situated on the production frontier; it takes positive value for the unit operating below the frontier. The distance function is interpreted as a measure of technical efficiency: a larger distance from the frontier means a lower technical efficiency. The properties of this function appear in LUNENBERGER (1992), CHUNG, FÄRE and GROSSKOPF (1997) and CHAMBERS, CHUNG and FÄRE (1998), and hence will not be recalled in this paper.

According to CHAMBERS, CHUNG and FÄRE (1998), directional distance function fully characterises the technology, in the sense that

$$(y, b) \in Y(x) \text{ if and only if } D_0(x, y, b; g) \geq 0. \quad (3)$$

That is, x can produce (y, b) if and only if the distance function is nonnegative.

CHAMBERS, CHUNG and FÄRE (1998) show that the directional output distance function is dual to the revenue function. This duality allows us to retrieve the output shadow prices by means of Shephard's lemma. Let us define the revenue function as

$$R(x, p, q) = \max_{(y, b)} \{py + qb \mid (y, b) \in Y(x)\}, \quad (4)$$

where $p = (p_1, p_2, \dots, p_Q) \in \mathfrak{N}_+^Q$ is the price vector for desirable outputs and $q = (q_1, q_2, \dots, q_R) \in \mathfrak{N}_-^R$ is the price vector for undesirable outputs. The revenue function $R(x, p, q)$ gives the largest feasible revenue that can be obtained from inputs, x , when the unit under investigation faces good output prices, p , and bad output prices, q . Undesirable outputs bear non-positive signs because bads generate a non-positive revenue.

Using (3), the revenue function can be equivalently written as

$$R(x, p, q) = \max_{(y, b)} \{py + qb \mid D_o(x, y, b; g) \geq 0\}. \quad (5)$$

This allows us to make revenue and distance functions appear in the same equation. The next step is to express $D_o(x, y, b; g)$ as a function $R(x, p, q)$.

Note that if $(y, b) \in Y(x)$, then $(y + \beta g_y, b + \beta g_b) = \{(y, b) + D_o(x, y, b; g)g\} \in Y(x)$. This is simply to say that if an output vector (y, b) is feasible, then the elimination of any inefficiency associated with that output vector by moving in the direction g is also feasible. Hence, we can write:

$$\begin{aligned} R(x, p, q) &\geq (p, q)\{y + D_o(x, y, b; g)g_y, b + D_o(x, y, b; g)g_b\} \\ &= py + qb + pD_o(x, y, b; g)g_y + qD_o(x, y, b; g)g_b \\ &= py + qb + (pg_y + qg_b) D_o(x, y, b; g). \end{aligned} \quad (6)$$

Rearranging the above expression, the relation between the directional output distance function and the revenue function becomes:

$$D_o(x, y, b; g) \leq [R(x, p, q) - (py + qb)] / [pg_y + qg_b]. \quad (7)$$

The directional distance function can also be recovered from the revenue function as

$$D_o(x, y, b; g) = \min_{(p, q)} \{[R(x, p, q) - (py + qb)] / [pg_y + qg_b]\}. \quad (8)$$

Applying the Shephard's lemma to the above expression, the normalized shadow prices of bad and good outputs are:

$$\frac{\partial D_o(x, y, b; g)}{\partial b} = \frac{-q}{(pg_y + qg_b)} \geq 0, \quad (9)$$

$$\frac{\partial D_o(x, y, b; g)}{\partial y} = \frac{-p}{(pg_y + qg_b)} \leq 0, \quad (10)$$

where q is the non-positive vector of shadow prices of undesirable outputs and p is the nonnegative vector of shadow prices of desirable outputs.

For two different outputs, e.g. y and b , it follows that their relative shadow price equals the corresponding ratio of distance function partial derivatives, which is equal to the marginal rate of technical transformation of output y into b , i.e., $\partial y / \partial b$.

$$\frac{q}{p} = \frac{\partial D_o(x, y, b; g) / \partial b}{\partial D_o(x, y, b; g) / \partial y} = \frac{\partial y}{\partial b} = MRTT_{y,b} \quad (11)$$

A high marginal rate of technical transformation implies that reducing b by one unit may only happen if y is reduced by several units. Converse holds true for a low marginal rate of transformation. Note that the relative shadow price, q/p , is no more normalised by $(pg_y + qg_b)$. Hence, the ratio q/p reflects the opportunity cost, or the trade-off between desirable y and undesirable b outputs (FÄRE et al., 1993).

Next, if at least one observed output price is known and one is willing to assume that it is equal to its shadow price, then absolute shadow prices may be retrieved following FÄRE et al. (1993). Namely, if one bad and one good output are produced, then the absolute shadow price of bad output is obtained as

$$q = p_o \frac{\partial D_o(x, y, b; g) / \partial b}{\partial D_o(x, y, b; g) / \partial y} \quad (12)$$

where p_o is the observed price of desirable output. The absolute shadow price q of undesirable output b reflects the marginal opportunity cost, in terms of forgone revenue, of an incremental decrease in the ability of freely dispose of the bad. Note that if the shadow price equals zero for a country, then this country can achieve a costless marginal reduction in its pollution emission (FÄRE, GROSSKOPF, LOVELL and YAISAWARNG, 1993). Finally, when the desirable output is measured directly in dollars, the relative shadow price q/p equals the absolute shadow price of CO₂ emissions.

The computation procedure outlined above allows us to obtain the estimates of shadow prices of pollution emissions that reflect the underlying technology. These are computed on the efficient boundary of output correspondence set. These shadow prices are equal to marginal costs of pollution abatement, but are not necessarily equal to the marginal benefit to society of pollution abatement. Indeed, the optimal (equilibrium) point of environmental degradation is not necessarily attained (see Figure 1). The estimation of the marginal benefit to society is not the objective of this paper.

Following CHUNG, FÄRE and GROSSKOPF (1997), we employ a mathematical programming technique to estimate non-parametric piecewise-linear production frontier, shadow prices and efficiency scores. This technique is presented in Appendix 1. This study uses a “horizontal” directional vector $g = (g_b, g_g)$, where g_b equals the mean value of the bad output in the sample and g_g is set to zero. Several tests using different orientation vectors g were performed, but the relative ranking of shadow prices of CO₂ across countries was not altered in a significant way.

4. Data

This study employs macro-economic cross-section data referring to 76 developed and developing countries observed during the year 1985. These include 30 low- and lower-middle income countries and 46 upper-middle and high-income countries.⁷ Either gross domestic product (GDP) or consumption has been alternatively considered as proxies for the desirable output. The undesirable output is carbon dioxide (CO₂). Each country is assumed to employ four inputs that are labour force, capital, arable land and energy. Data on GDP and consumption are expressed in purchasing power parity U.S. dollars and refer to the year 1985. Information on GDP, CO₂ emissions, labour force, arable land and energy consumption has been collected in the World Development Indicators (WDI) database. Data on consumption come from the Penn World Table (PWT, mark 5.6).

7 This classification is based on the United Nations International Comparison Program (ICP), see Appendix 2.

Table 1: Descriptive Statistics

Variable	Units	Mean	St. Dev.	Min.	Max.
GDP	Mio. U.S.\$	210511	521378	3781	4022089
Consumption	Mio. U.S.\$	132504	339261	1733	2657178
CO ₂	Thousands of tons	176342	565077	941	4451789
Capital stock	Mio. U.S.\$	593559	1442513	10437	10871285
Labour force	Thousands of workers	24322	74409	129	500'723
Energy consumption	Thousand of tons (equiv. oil)	75262	225378	1075	1781709
Arable land	Thousands of hectares	13089	31661	3	187765
GDP per capita	U.S.\$	5924	5063	325	17508
CO ₂ per capita	Tons	4.34	5.08	0.85	23.69
Pollution intensity	Tons of CO ₂ / thousand of U.S.\$	0.66	0.52	0.09	3.23

To measure the CO₂ emissions, the WDI consider the pollution stemming from burning of fossil fuels and cement manufacturing. These comprise CO₂ emissions due to utilisation of solid, liquid, and gas fuels and gas flaring. Input “energy consumption” refers to primary energy, natural gas, solid fuels, and primary electricity. The energy obtained from all these sources is converted into oil equivalent. The arable land includes the land under temporary crops, temporary meadows for mowing or for pasture, land under market or kitchen gardens, and land temporarily fallow. Land abandoned as a result of shifting cultivation is excluded. Data on physical capital stock come from NEHRU and DHARESHWAR (1993) and are based on the perpetual inventory method. This capital stock variable is considered to be the best currently available one (PAPAGEORGIOU, 2003). As the capital stock data are initially expressed in constant 1987 U.S.\$, we computed the physical capital stock by multiplying the GDP (in 1985 U.S.\$) by the ratio of physical capital stock (in 1987 U.S.\$) to the GDP (in 1987 U.S.\$). Descriptive statistics for all output and input variables, as well as some additional ratios discussed further in the text are presented in Table 1.

5. Empirical Results

According to theoretical models summarised in Section 2, existence of the EKC might depend on the nature of the relationship between marginal pollution abatement cost and income. If pollution abatement costs rise when income grows, this contributes to the rise of emissions. On the contrary, diminishing marginal opportunity costs of pollution might constitute a “good” news, even if this is not a sufficient condition to insure that emissions decrease with income, as long as the demand for emission reduction is ignored. The first part of this section examines the cross-country variations in the shadow prices of CO₂ emissions. The second part reports the “win-win” situations existing for some countries where the CO₂ emissions might be reduced without sacrificing any quantity of desirable output.

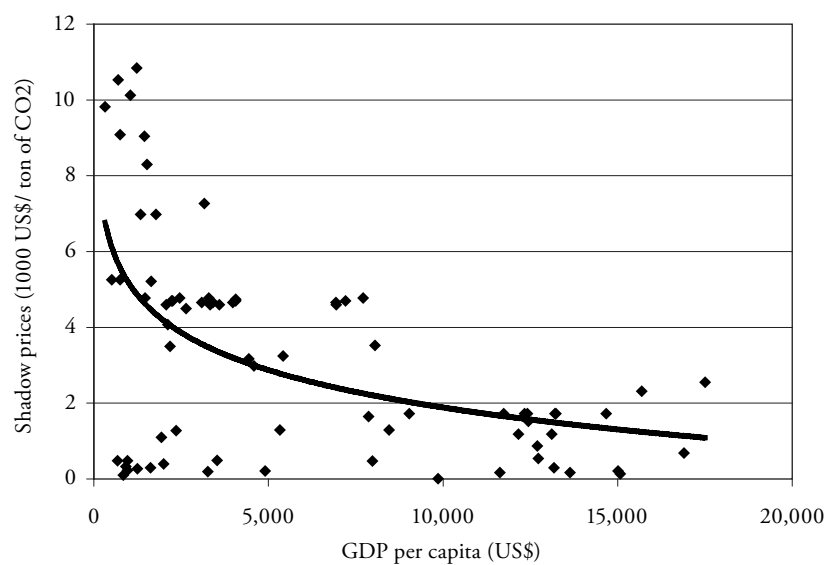
5.1. *Marginal Opportunity Costs of Pollution Abatement*

Marginal opportunity costs of abatement are computed according to the procedure outlined in Section 3. The opportunity cost specific to a country equals the ratio of its shadow prices q/p . The estimates show that shadow prices of CO₂ diminish as income per capita grows: the high-income countries have lower shadow prices than the less developed ones. Hence, the developed economies would have to undergo a smaller loss of consumption or GDP if the last unit of the CO₂ pollution had to be eliminated. Figure 3 depicts the negative relationship between shadow price estimates and GDP per capita.⁸ Table 2 reports some descriptive statistics on the shadow prices by income group. More details regarding the estimated shadow prices per country are available upon request. The negative relationship between the income/consumption per capita and the marginal cost of CO₂ abatement was also assessed by means of OLS regressions reported in Appendix 3 (Tables A1 and A2).

Deterministic mathematical programming estimation procedures might be sensitive to outliers (WILSON, 1995). If some atypical units define some parts of production frontier, estimations might reveal unstable across countries and alternative data sets. Therefore, an outlier analysis was performed by regressing outputs on inputs and examining the leverage plots and Cook distances. Five outliers – China, United States, India, Japan, and Germany – were identified.

8 In Figure 3, GDP is employed as a measure of desirable output. The figure with consumption as a measure of desirable output is available upon request.

Figure 3: Shadow Prices Estimates vs. GDP per Capita



Note: GDP is used as a measure of desirable output.

Table 2: Shadow Prices Estimates by Income Group

Desirable output: GDP	Average shadow price	Highest shadow price	Lowest shadow price
Low-income countries	5.22 (4.33)	10.83	0.10
Lower-middle income countries	3.83 (2.38)	8.03	0.29
Higher-middle income countries	3.27 (1.96)	7.27	0.01
High-income countries	1.16 (0.77)	2.55	0.13
Desirable output: Consumption			
Low-income countries	4.74 (3.63)	11.65	0.22
Lower-middle income countries	2.51 (2.04)	6.68	0.17
Higher-middle income countries	1.09 (0.78)	3.52	0.01
High-income countries	0.60 (0.46)	1.29	0.07

Note: standard deviations are in parenthesis.

These observations might have a considerable influence on the estimated production frontier. Indeed, all of them belong to 24 fully efficient economies located on efficient frontier.⁹ In order to check the robustness of our results, estimations have been run again on a restricted sample excluding these outliers. The negative relationship between shadow prices and GDP per capita was conserved and even became stronger.

The robustness of our findings with respect to choice of the data set was also investigated. An alternative data set was created where capital data¹⁰ come from the Penn World Table (PWT, mark 5.6). These latter are considered as particularly adequate for cross-country comparisons. Availability of capital data in PWT reduces the sample size to 57 countries. Still, the prior negative relationship holds true. However, as this alternative sample counts only 15 low- and lower-middle income countries, evidence of a negative relationship is somewhat weaker.

Shadow prices for alternative directional vectors $g = (g_y, g_b)$ was also estimated. By doing so, absolute values of shadow prices were changed, but their relative ranking across countries and income levels varied very little. Robustness of results was also controlled by including additional inputs (e.g., energy production) or by excluding some inputs (arable land). In either case, the negative relationship between marginal abatement cost of carbon emissions and the countries' GDP per capita remains unchanged. Finally, shadow prices for alternative years (1980 and 1990) were estimated without altering this pattern.

5.2. Zero-Cost Abatement Opportunities

The second set of results concerns efficiency scores β resulting from solution of mathematical programming problem given by the set of equations (A1) in Appendix 1. Economies with zero-cost opportunities of reducing carbon dioxide emissions are identified. An efficiency score larger than zero indicates the presence of inefficiencies in the production process. For inefficient countries, there exist possibilities to pollute less without sacrificing desirable output. The amount of CO₂ that could have been avoided without reducing the desirable output by country i (Δb_i) is computed according to the following formula (CHUNG, FÄRE and GROSSKOPF 1997):

9 Furthermore, these countries are fully efficient but dominate no other one, in the sense that no inefficient economies are comparable to them as to the inputs/outputs mix.

10 Capital data are computed by multiplying the capital per worker by the labour force. These data do not take into account the residential capital stock (housing).

$$\Delta b_i = b_i - (b_i - \beta_i g_b), \quad (13)$$

where b_i is the observed quantity of carbon emission in country i , β_i is the efficiency score of country i and g_b is the directional vector for the bad output (equal to the average value of CO₂ emissions in the sample). Note that $(b_i - \beta_i g_b) = b_i^*$ equals the estimated minimum attainable level of CO₂ emissions for country i .

13% of global carbon dioxide emissions could be avoided at no cost in terms of forgone GDP, according to the estimations performed on the full sample. This percentage rises to 30% when the five outliers are excluded from the estimation. The difference is so important because the five outliers are responsible for a very large part of the CO₂ emissions in the sample (nearly 60%).¹¹ If consumption is used as a proxy for the desirable output, the zero-cost reductions amount to 28% of the CO₂ emissions. Detailed results figure in Appendix 3 (Table A3).

The location of the zero-cost reductions does not follow a particular pattern across income levels, as depicted in Figure 4. The zero-cost reduction possibilities are however positively correlated with pollution intensity (ratio of CO₂ emissions to GDP), according to Figure 5. This result supports the hypothesis that the marginal abatement costs are low when pollution load is high (PEARCE, 1976).

6. Discussion

This paper evaluates the economic burden that reduction of carbon dioxide emissions might generate, and relates the opportunity cost of CO₂ abatement to the degree of economic development, as measured by the GDP per capita. In a cross-section data set of 76 developing and developed countries, we found that marginal cost of CO₂ abatement diminishes as the country's per capita GDP grows. The same relationship was found between the CO₂ abatement costs and per capita CO₂ emissions. This could be expected, because GDP per capita and CO₂ emissions per capita are strongly correlated. To estimate shadow prices, all countries were assumed to be situated on the boundary of the output correspondence set. Otherwise stated, shadow prices were computed under the hypothesis of no technical inefficiencies in production process.

11 The percentage of efficient countries in the sample varies very little due to exclusion of five outliers. Indeed, it equals 36.8% for the whole sample, and 35.2% for the restricted sample without outliers.

Figure 4: Zero-cost Emission Reductions (% of Total National Emissions)
vs. GDP per Capita

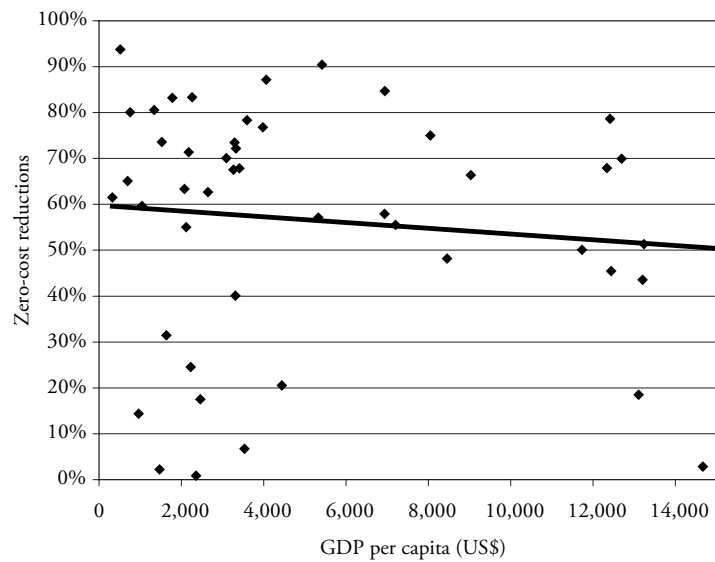
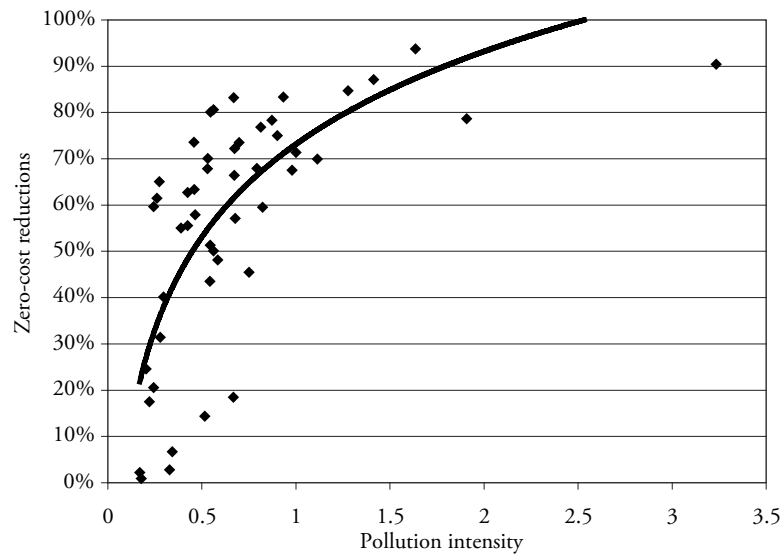


Figure 5: Zero-cost Emission Reductions (% of Total National Emissions)
vs. Pollution Intensity



Marginal opportunity cost of carbon dioxide abatement diminishing with CO₂ per capita and GDP per capita constitutes empirical findings which are in line with economic theory. Indeed, BAUMOL and OATES (1998) postulate a negative relationship between marginal abatement costs of pollution emissions and environmental degradation. Environmental degradation being more important in the most developed countries than in the least developed ones, one would expect the abatement costs of pollution to fall as development proceeds. Therefore, our estimations of shadow prices for carbon dioxide confirm theoretical relationship between pollution emissions and development.

Marginal costs of CO₂ abatement decreasing with income, one could expect, *ceteris paribus*, to observe diminishing levels of CO₂ emissions in the high-income countries. Carbon dioxide abatement becoming cheaper as economic development proceeds, the empirical findings reported in Section 5 seem to be favourable to emergence of the Environmental Kuznets Curve. However, most available empirical evidence shows no inverted U-shaped relationship for the CO₂ emissions, but a monotonically increasing pattern of emissions with income (AGRAS and CHAPMAN, 1999; PERRINGS and ANSUATEGI, 2000). How this is possible? We suppose that carbon emissions might rise as development proceeds because society might perceive no benefit in reducing CO₂. Explanations of no EKC for carbon dioxide may lie on the demand-for-environmental-quality side, rather than on the cost-of-pollution-reduction side. In other words, decreasing macro-economic abatement costs lead to no measure because of the insufficient willingness to pay to abate carbon emissions.

According to our empirical findings, several countries are not situated on the best-practice production frontier. These economies are characterised by some degree of technical inefficiency in the process of transforming inputs into (desirable and undesirable) outputs. In this paper, the amounts of CO₂ emissions that could be avoided without reducing the desirable output (i.e., zero-cost reductions) were estimated. These latter are not correlated with GDP per capita, but are positively correlated with pollution intensity (ratio of CO₂ emissions to GDP).

If some degree of technical inefficiency is present in production process, pollution abatement does not necessarily imply a trade-off between desirable and undesirable outputs. This abatement could be carried out at zero marginal cost. By estimating shadow prices on the efficient boundary of production possibilities set, technical inefficiencies were not taken into account. Therefore, shadow prices of CO₂ for inefficient countries could be equal to zero, whereas positive shadow prices were estimated on the efficient production frontier. However, the degree of technical efficiency and the GDP per capita being uncorrelated, we argue that this caveat in the estimation of shadow prices does not alter the conclusion

on negative correlation between CO₂ abatement costs and GDP per capita. It is possible to include information on technical inefficiencies in the estimation of shadow prices (LEE, PARK and KIM, 2002), and this approach constitutes an interesting topic for future research.

Positive correlation between the estimated amounts of zero-cost CO₂ reductions and pollution intensities (which equals the ratio of CO₂ emissions to GDP) is in line with theoretical arguments. Indeed, PEARCE (1976) postulates that when pollution load is high, low-cost pollution abatement opportunities are large.

The above findings are however challenged by the belief, even somewhat uncertain,¹² that carbon dioxide abatement costs – and pollution abatement costs in general – are lower in less developed economies than in more developed ones. This belief emanates from the so-called bottom-up and top-down models, which constitute the core of IPCC (2001) study. We argue this contradiction is spurious, and arises from the fact that our estimates are concerned with different type of abatement costs than those discussed in IPCC (2001).

Existing studies of greenhouse gases abatement costs (WEYANT, 1993) rely on *projections* for the future of the likely costs of alternative levels of control of GHG emissions, as compared to the business-as-usual scenario. In IPCC (2001), bottom-up models calculate the costs of adopting the technological option necessary for reducing emissions by a given amount. Top-down approaches determine the abatement costs equal to the amount of carbon tax that will push economy towards achieving the targeted emission reduction. Unlike these studies, we estimate the costs of *immediate* reductions of carbon emissions measured in terms of consumption or GDP forgone. In particular, we assume that to reduce pollution, it is necessary to reduce the production of desirable outputs. Hence, the definition of our abatement costs differs from IPCC.

According to IPCC (2001), no correlation exists between the amount of carbon tax necessary to reach a certain emission target, and the GDP loss, or opportunity cost, faced by the country. As shown by COPPEL (1993), a global carbon tax imposed identically to all countries would result in a disproportionate burden on developing economies. Furthermore, usual abatement costing studies refer to the reduction of *future* emissions as compared to a business-as-usual scenario, while our measure rests on *current* emissions. This constitutes another major difference

12 See CHAPMAN and KHANNA (2000) on the uncertainty of the theoretical and empirical basis supporting the existence of higher (lower) abatement costs in richer (poorer) countries.

between our results and the IPCC's (2001) estimates.¹³ Last, but not least, top-down models rest on multiple hypotheses (and uncertainties) regarding the economic and demographic growth rates, the availability and cost of future backstop technologies, and the existence of transition costs.¹⁴ Our estimation procedure needs no such assumptions, because it is based on the observed choices of production mixes operated by countries.

The results presented above should be interpreted with some caution with respect to following issues. First, our findings do not imply a *causality* relationship between the growth of income (or consumption) per capita and the decay of marginal opportunity costs of abatement. The existence of a negative *correlation* that we found does not rule out the possibility that for some countries, abatement costs do not fall as development proceeds. Developing countries may be so different, as to their technological regimes, from the developed ones, that they would not follow the same development path. Further analysis involving panel data would be very beneficial to study this issue.

Second, even if marginal opportunity costs of CO₂ abatement are generally lower in the developed economies than in the developing ones, this relationship does not hold for all countries. For some developing economies, estimated abatement costs are lower than those estimated for the high-income economies, and vice-versa.

Third, results regarding the existence of zero-cost opportunities of CO₂ reductions should be considered with some caution. Indeed, the costs of transition from the current "dirty" production process to a "cleaner" and more efficient one are ignored. These results give no information regarding the optimal path of moving towards the efficient frontier. Uncertainty may reveal even greater if the production frontier is not static through time, but moves due to technological progress. In order to get further insight into this question, computation of Malquist index could be valuable (ZAIM and TASKIN, 2000; KUMAR and KHANNA, 2002).

Finally, existence of one unique technological regime pertaining to all economies under investigation was assumed. However, different countries may use different technologies corresponding to different production frontiers (TYTECA,

13 The cost of meeting any emission-reduction targets can be reduced if it is phased in over a longer period of time. For this reason, our estimates – which are concerned with immediate emission reductions – exhibit abatement costs that are higher than those reported in IPCC (2001). The latter are concerned with future emission reductions distributed over more or less long periods of time.

14 According to CHICHILNISKY (1993), such models rather assume than establish that developing countries have lower abatement costs.

1995). Moreover, production frontiers might be influenced by exogenous conditions such as climate, geographical situation, historical factors, traffic volume, etc. While the hypothesis of one unique production frontier pertaining for all economies might be reasonable enough because each combustion process generates CO₂ emissions, the issue of exogenous conditions needs further investigation.

7. Conclusions

The purpose of this paper was to advance an evidence-based approach to understand the impact of income growth on the marginal cost of pollution abatement. We empirically estimated marginal abatement costs of carbon dioxide emissions for 76 developing and developed countries. These estimates – carried out by means of directional distance functions – were then related to the degree of economic development, and to theoretical and empirical literature on the Environmental Kuznets Curve.

The estimated pattern of marginal abatement costs of CO₂ relative to the GDP per capita shows that income is negatively associated with marginal opportunity cost of carbon dioxide abatement. The main conclusion drawn from this study is that immediate reductions of carbon dioxide emissions are on average cheaper, in terms of desirable output forgone, in the high-income countries than in the low-income ones. According to AGRAS and CHAPMAN (1999) and PERRINGS and ANSUATEGI (2000), carbon dioxide emissions do not follow the inverted U-shaped EKC pattern relative to national income, but increase with income. Our findings offer an insight into reasons of no EKC pattern in carbon emissions. Ever increasing emissions are *not* explained by growing abatement costs of carbon dioxide, but they might be rather due to a low society's demand for carbon reductions.

Regarding the performance of transformation of available resources into desirable and undesirable outputs, low-income economies were not found to be systematically less efficient than those characterised by high income per capita. Therefore, one should be cautious when asserting that numerous zero-cost pollution abatement opportunities are available in the developing world. Empirical evidence presented above contradicts this assertion (IPCC, 2001). Furthermore, the amount of CO₂ emissions that could be abated at zero cost is larger in countries with high pollution intensities.

From the perspective of the Kyoto Protocol implementation, our findings justify the exclusion of developing economies from the obligation to adopt binding

carbon dioxide emission targets. If the abatement had to be carried out immediately, empirical evidence suggests that low-income countries would incur higher opportunity costs of abatement than high-income countries. Therefore, binding targets for the developing world would be unfair.

To summarise, this paper pursue several objectives. First, as suggested by CHAPMAN and KHANNA (2000), it addresses the quite unexplored issue of empirical estimation of carbon dioxide abatement costs. Next, attempts are made to fill the gap between theoretical explanations of the causes of Environmental Kuznets Curve and empirically oriented research. Last, but not least, directions for further research on the EKC and shadow prices of carbon dioxide are suggested. In order to understand why the EKC does not emerge for the emissions of carbon dioxide, it would be interesting to analyse the evolution of the willingness to pay for abating these emissions when income grows. Estimation of shadow prices on the basis of panel data and analysis of other pollutants would constitute interesting directions for further research. Regressing efficiency scores on exogenous variables might help us to understand why some economies are technically efficient, and some others are not. In turn, this may explain the reasons of emergence of zero-cost pollution abatement opportunities. Finally, estimation of shadow prices taking into account the degree of country's inefficiency, along the lines proposed by LEE, PARK and KIM (2002), is also a promising direction for further work.

Appendix 1

A1.1. Assumptions on the Output Correspondence Set

- A1. There is no free lunch: $Y(0) = \{0, 0\}$, i.e., zero inputs yield zero outputs.
- A2. Doing nothing is feasible: $(0, 0) \in Y(x) \forall x \in \mathfrak{R}_+^p$. This axiom guarantees that inaction is possible, i.e., given any input vector it is always possible to produce nothing.
- A3. Scarcity: $Y(x)$ is compact for each $x \in \mathfrak{R}_+^p$, i.e., only finite output can be produced given finite inputs. This is usually referred as the basic scarcity problem of economics.
- A4. If $(y, b) \in Y(x)$ and $x' \geq x$ then $(y, b) \in Y(x')$, i.e., inputs are freely disposable. This assumption says that if it is possible to produce a given amount of outputs (y, b) using the amount of inputs x , then it is also possible to produce the same amount of outputs with a larger amount of inputs x' .

Joint production of goods and bads:

- A5. If $y \in Y(x)$ and $0 < \theta \leq 1$, then $\theta y \in Y(x)$, i.e., weak disposability of bad outputs. This property says that for a given input vector, proportional (radial) contractions of outputs are feasible.
The weak disposability of a particular output implies that this output is undesirable (e.g., pollution) and its restriction is costly in the sense that it uses resources which otherwise could have been used to maintain or increase desirable outputs. Weak disposability captures the idea of trade-off between pollution and intended outputs.
- A6. If $y \in Y(x)$ and $y' \leq y$, then $y' \in Y(x)$, i.e., desirable outputs are freely disposable. This assumption says that if it is possible to produce a given amount of desirable output y using the amount of inputs x , then it is also possible to produce a smaller amount of desirable output y' with the same amount of inputs x .
- A7. $(y, b) \in Y(x)$ and $b = 0$, then $y = 0$, i.e., for a given input vector, if bad output is zero, then the same must hold true for good output. This is called the null-jointness property. This assumption is intended to capture the inevitability of pollution generation in the process of production of intended outputs. In other words, if one wishes to produce good output, some bad output will also be produced.
- A8. $Y(x)$ is convex.

A1.2. Estimation Procedure

Following CHUNG et al. (1997), we employ a mathematical programming technique to estimate non-parametric piecewise-linear production frontier. Denoting by N the total number of countries under investigation, the production frontier for the country A is estimated by solving the following mathematical programming problem:

$$D_o(x, y, b; g) = \max \beta \quad (A1)$$

subject to

$$\sum_{i=1}^N z_i y_{i,q} \geq \delta(y_{A,q} + \beta g_{y_q}), \quad q = 1, \dots, Q,$$

$$\sum_{i=1}^N z_i b_{i,r} = \delta(b_{A,r} + \beta g_{b_r}), \quad r = 1, \dots, R,$$

$$\begin{aligned}
\sum_{i=1}^N z_i x_{i,p} &\leq x_{A,p}, & p=1,\dots,P, \\
\delta &\geq 1, \\
\beta &\text{ is free,} \\
z_i &\geq 0 \quad \forall i=1,\dots,N.
\end{aligned}$$

The parameter β , or the technical efficiency score, equals zero for efficient economies and is positive for the inefficient ones. The vector $g = (g_b, g_y)$ defines the orientation in which is measured the distance to the frontier. The program should be solved N times and leads to the estimation of shadow prices and efficiency scores for each country. The coefficients z_i , $i = 1, \dots, N$ are called intensity variables. The variable returns to scale technology – i.e., the least restrictive hypothesis – is obtained by adding the constraint

$$\sum_{i=1}^N z_i = 1.$$

The inequalities in the constraints for inputs x make them freely disposable, and the same holds true for the good outputs y . Weak disposability of bad outputs b is imposed by the strict equalities in the bad output constraints and the “weak disposable parameter” δ which allows for proportional contractions of (y, b) . (A1) may be easily transformed into a linear programming problem by defining the new intensity variables $\gamma_i = z_i / \delta$ for $i = 1, \dots, N$. The shadow prices p and q associated to the primal constraints for good and bad outputs are obtained as part of usual linear programming solution's output.¹⁵

15 The shadow price on a particular constraint of a linear programming problem represents the change in the value of the objective function per unit increase in the right hand-side value of the constraint (BRADLEY, HAX and MAGNANTI, 1977, p. 20). In our case, the objective function is the directional distance function, and the good and bad outputs appear in the right hand-side parts of the constraints – hence, the shadow prices equal the partial derivatives of $D_s(x, y, b; g)$.

Appendix 2. Countries Included in the Sample

The countries analysed in this paper belong to four income groups defined by the United Nations International Comparison Programme (ICP). The GDP is measured in real terms, in 1985 U.S.\$ per capita. The groups are the following:

Group 1 – Low-income countries (GDP < \$1,500): Bangladesh, China, Congo Dem. Rep., Ivory Coast, Ghana, Haiti, India, Indonesia, Kenya, Mozambique, Nigeria, Pakistan, Senegal, Sri Lanka, Sudan, Zambia.

Group 2 – Lower middle-income countries (\$3,000 > GDP > \$1,500): Bolivia, Cameroon, Dominican Republic, Ecuador, Egypt Arab Rep., El Salvador, Guatemala, Honduras, Jamaica, Morocco, Nicaragua, Philippines, Thailand, Zimbabwe.

Group 3 – Upper-middle income countries (\$10,000 > GDP > \$3,000): Algeria, Argentina, Brazil, Chile, Colombia, Costa Rica, Cyprus, Greece, Iran Islamic Rep., Ireland, Israel, Jordan, Korea Rep., Kuwait, Malaysia, Mexico, Panama, Paraguay, Peru, Portugal, South Africa, Spain, Trinidad and Tobago, Tunisia, Turkey, Uruguay, Venezuela.

Group 4 – High-income countries (GDP > \$10,000): Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Iceland, Italy, Japan, Luxembourg, Netherlands, New Zealand, Norway, Sweden, Switzerland, United Kingdom, United States of America.

Appendix 3. Estimation Results

Table A1: Regressions of Shadow Prices (Measure of Desirable Output: GDP per Capita)

Variables	1	2	3	4
Log (GDP per capita)	-1.43 (-4.34)			0.09 (0.15)
Log (CO ₂ emissions per capita)		-1.18 (-5.34)		-1.23 (-2.92)
Log (Pollution intensity) = Log(CO ₂ /GDP)			-1.78 (-4.01)	
Constant	15.02 (5.13)	4.06 (10.67)	2.09 (5.57)	3.37 (0.72)
Number of observations	76	76	76	76
F-statistic	18.83	28.48	16.10	14.12
Adjusted R ²	0.26	0.34	0.19	0.34

Note: Robust standard errors are in parenthesis.

Table A2: Regressions of Shadow Prices (Measure of Desirable Output: Consumption per Capita)

Variables	1	2	3	4
Log (GDP per capita)	-1.44 (-5.43)			0.11 (0.25)
Log (CO ₂ emissions per capita)		-1.19 (-6.29)		-1.26 (-3.45)
Log (Pollution intensity) = Log(CO ₂ /GDP)			-1.81 (-4.22)	
Constant	13.86 (5.83)	2.81 (8.90)	0.80 (2.87)	1.93 (0.54)
Number of observations	76	76	76	76
F-statistic	29.47	39.62	17.79	19.81
Adjusted R ²	0.36	0.47	0.27	0.48

Note: Robust standard errors are in parenthesis.

Table A3: Carbon Abatement Opportunities as Percentage of Total Emissions

Country	Kt of CO ₂	% of total emissions	Country	Kt of CO ₂	% of total emissions
Algeria	54,384	77%	Morocco	9,822	55%
Argentina	56,518	58%	Mozambique	705	61%
Australia	155,975	70%	Netherlands	61,561	45%
Austria	23,559	44%	New Zealand	10,810	50%
Bolivia	3,033	74%	Nigeria	65,493	94%
Chile	14,795	68%	Norway	564	3%
Cote d'Ivoire	5,978	81%	Pakistan	6,772	14%
Denmark	37,596	60%	Panama	176	7%
Dominican Republic	4,532	63%	Peru	7,671	40%
Ecuador	15,994	83%	Philippines	5,149	18%
El Salvador	18	1%	Portugal	16,999	56%
Finland	32,553	68%	South Africa	234,905	85%
Germany	125,556	18%	Spain	91,398	48%
Ghana	1,922	60%	Sri Lanka	88	2%
Greece	40,047	66%	Sweden	30,860	51%
Guatemala	864	25%	Thailand	30,807	63%
Honduras	600	31%	Trinidad and Tobago	18,675	90%
Iran, Islamic Rep.	115,645	78%	Tunisia	8,359	70%
Ireland	19,239	75%	Turkey	81,400	72%
Jamaica	3,597	71%	Uruguay	670	21%
Jordan	5,713	68%	Venezuela, RB	85,702	87%
Kenya	2,451	65%	Zambia	2,204	80%
Luxembourg	6,842	79%	Zimbabwe	8,535	83%
Malaysia	26,434	73%			
Mexico	155,587	57%	TOTAL	1,688,758	13%

Countries with no zero-cost CO₂ abatement opportunities:

Bangladesh, Belgium, Brazil, Cameroon, Canada, China, Colombia, Congo Dem. Rep., Costa Rica, Cyprus, Egypt Arab Rep., France, Haiti, Iceland, India, Indonesia, Israel, Italy, Japan, Korea, Rep., Kuwait, Nicaragua, Switzerland, Sudan, Senegal, United Kingdom, United States, Paraguay.

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SUMMARY

This paper examines how the marginal CO₂ abatement costs vary throughout stages of economic development, and how these variations may be related to the Environmental Kuznets Curve (EKC) hypothesis. By assuming the existence of a technological link between production of desirable outputs and pollution, shadow prices of carbon emissions are estimated for 76 developing and developed countries. The results show that immediate carbon reductions are more costly in terms of desirable output forgone in the developing economies than in the developed ones. Several interpretations of this finding are finally proposed.

ZUSAMMENFASSUNG

Die vorliegende Studie analysiert die Grenzkosten für die Senkung der CO₂-Emissionen in 76 Industrie- und Entwicklungsländern und untersucht den Zusammenhang zwischen diesen Kosten und dem Wirtschaftswachstum. Die Resultate werden ebenfalls mit der Umwelt-Kuznets-Kurve in Bezug gebracht. Die Schattenpreise (*shadow prices*) der CO₂-Emissionen werden unter Annahme eines technologischen Zusammenhanges zwischen der Produktion des gewünschten Outputs und der Umweltverschmutzung berechnet. Unsere Ergebnisse belegen, dass die Grenzkosten für die Senkung der CO₂-Emissionen mit steigendem Pro-Kopf-Bruttoeinkommen abnehmen. Verschiedene Interpretationen dieser Resultate werden vorgestellt.

RÉSUMÉ

Cet article étudie l'évolution des coûts marginaux de réduction des émissions de CO_2 en fonction du niveau de développement économique. Il a pour objectif de compléter les évidences empiriques à l'égard de la Courbe Environnementale de Kuznets. Les *shadow prices* des émissions de CO_2 sont déterminés en postulant l'existence d'un lien technologique entre la production des outputs désirés et les émissions polluantes. Les résultats montrent que la relation entre les coûts marginaux de réduction des émissions de CO_2 et le revenu par habitant est négative. Plusieurs interprétations de ce résultat sont finalement proposées.