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

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Abstract

The emissions of carbon dioxide (CO_2) might be responsible for the global climate change. It is not clear whether their amount follows an inverted U-shaped pattern relative to national income per capita, a relationship called the Environmental Kuznets Curve (EKC). Neither it is clear why it should or should not. This paper examines how marginal CO_2 abatement costs vary throughout stages of economic development, and how these variations may contribute to the emergence of EKC. Prior empirical work on pollution abatement costs is scarce, and mostly unrelated to EKC literature. Our objective is to reduce the gap between theoretical explanations of the EKC and empirically oriented research. By assuming the existence of a technological link between production of desirable outputs and pollution, shadow prices of the CO_2 emissions are estimated for 76 developing and developed countries. The results show that reducing the CO_2 is more costly in terms of desirable output forgone in the developing economies than in the developed ones. Interpretations of our findings in the light of the EKC theory are offered and implications for the policy making are discussed.

Keywords: Carbon dioxide emissions, Marginal abatement costs, Environmental Kuznets Curve, Directional distance function

JEL Classification: C61, Q53, Q56

1. Introduction

A lasting question in environmental economics addresses the existence of a relationship between environmental quality and national income. A trend of research examines the existence of an inverted U-shaped curve, called the Environmental Kuznets Curve (EKC, hereafter), expressing the relationship between a measure of economic affluence – e.g., Gross Domestic Product (GDP) per capita – and some indicators of environmental quality

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(Grossman and Krueger, 1993; Shafik and Bandyopadyay, 1994). In case the EKC exists,[1] some authors argue that economic development by itself is a panacea for environmental degradation. According to Beckerman (1992), more economic growth leads to cleaner environment. However, it is not entirely clear why the EKC should exist or not, and by which economic factors and mechanisms it might be explained.

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 by the current state of technology. Obviously, the latter depends on the degree of economic development. Hence, 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 (i.e., the EKC).

The purpose of this paper is to advance an evidence-based approach to understand the impact if income growth on the marginal cost of pollution abatement, which might influence the emergence of the EKC. 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 (CO_2) 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 CO_2 reduction opportunities?; and Why the empirical evidence regarding the existence of the EKC for CO_2 emissions is so controversial? To answer theses questions, the relationship between the marginal abatement costs of CO_2 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.[2] 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 more rare. Bluffstone (1997), Hartman et al. (1994), and Dasgupta et al. (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 CO_2 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.

[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 et al., 2000; Lieb, 2002).

[2] Traditional econometric "reduced-form approach" investigates the existence of the EKC for cross-section or panel data set. Either emissions per capita or emissions per unit of GDP (emission intensity) are considered to be function of the GDP per capita and its multiples. Some other explanatory variables such as prices, socio-economic variables, time dummies, etc., are often taken into account.

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 (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 CO_2 abatement as national income grows. Developed countries are less penalised by pollution reductions, in terms of the GDP or consumption forgone, than the developing ones. The quantities of CO_2 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 CO_2 emissions is interesting for at least two reasons. First, empirical evidences regarding the existence of the EKC for the CO_2 emissions are mixed.[3] Therefore, deeper investigations of the reasons for the emergence of the EKC are useful. Second, as carbon dioxide – a greenhouse gas – 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[4] relies 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 Environmental Kuznets Curve. 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 arguments underlying the existence of the EKC fall into two broad groups. First, the EKC may be due to the structural change that accompanied the 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 et al., 1995). Hettige et al. (1992) and Suri and Chapman (1998) further argue that this transition to clean service economies (called "composition effect" in the EKC literature) is reinforced by the displacement of pollution-intensive activities from developed to developing countries. They

[3] 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, some studies do find an inverted U-shaped curve (Dijkgraff and Vollebergh, 2001; Carson et al., 1997).

[4] The Kyoto Protocol is an international agreement adopted in 1997 in Japan. The Protocol sets binding emission targets for developed countries that would reduce their emissions on average 5.2% below their 1990 levels for 2008-2012.

explain this process by the existence of tighter environmental regulations in the developed economies as compared to the developing ones ("pollution heaven" hypothesis).

The second theoretical argument underlying the existence of the EKC focuses on the demand for environmental quality. According to Beckerman (1992) and Chaudhuri and Pfaff (2002), the demand for environmental quality increases with income, resulting in positive income elasticity for environmental quality.[5] 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 of, environmental protection. According to Vogel (2000) and Panayotou (1997), a high level of environmental awareness is likely to arise in developed countries due to visible and large environmental damages caused by pollution. In addition to prior explanations, 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 income of their citizens increases.

While the analysis of the demand for environmental quality is interesting and informative, the analysis of the supply side of the environmental quality is also important, but has deserved little attention in the existing literature. By the supply side we mean the opportunity cost of environmental protection in terms of production forgone. This latter is also susceptible to vary through stages of development, and therefore might either cancel or amplify the demand effect. This concern is obvious in standard economic theories: pollution abatement is worthwhile only as long as the difference between the total social benefit derived from a reduction of pollution and the cost of achieving such a reduction is positive (Pearce, 1977; Burrows, 1979).

2.2. Review of Some Theoretical Models

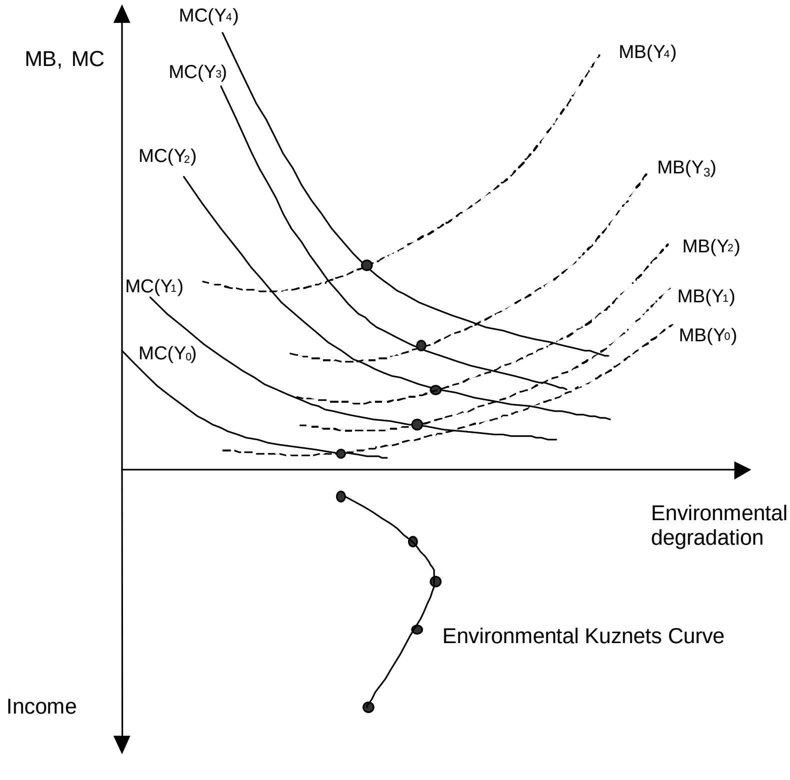
Several models giving rise to the EKC are derived from the theoretical arguments presented above. We shortly review some theoretical models taking into account the pollution abatement opportunities. Munasinghe (1999) considers a series of equilibriums resulting from interactions between the demand and supply of environmental quality. He shows how these interactions can lead to the emergence of the EKC. The analysis is based on standard theoretical framework that may be summarised by means of the marginal benefit (MB) curve and the marginal abatement cost (MC) curve (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

[5] Ansuategui et al. (1998), Neumayer (1998), Cole (2000), and De Bruyn (2000) argue that environmental quality is a luxury good.

degradation point is approached. The optimal point of environmental degradation is obviously given by the intersection of the MC and MB curves, where the marginal cost and benefit of pollution abatement are equal.

Extending this MC-MB framework by assuming that income level may affect the MC and MB curves, Munasinghe (1999) shows that several types of relationship between economic affluence and environmental degradation might emerge. The EKC arises under conditions that when income grows, the MC as well as the MB curves shift upwards, the MC at a decreasing pace, the 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. It is straightforward that the displacement of the MC curve with income might either contribute or not to the emergence of the EKC. For example, if the marginal cost of abating the pollution decreases at high levels of income, an inverted U-shaped pollution path might result even if the MB curve does not shift upwards as income grows.

The assumption of the upward shift of the MB curve which happens 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 checked empirically. This paper proposes to test this latter for the CO_2 emissions.



Note: $Y_0 < Y_1 < Y_2 < Y_3 < Y_4$
Source: Munasinghe (1999)

Figure 1. Deriving the Environmental Kuznets Curve

Alternative models of theoretical micro-foundations of the EKC taking into account the role of abatement costs are proposed by Vogel (1999), Selden and Song (1995) and Andreoni and

Hilton (2001). Vogel (1999) shows that the increasing willingness to pay for environmental quality, combined with the constant efficiency of abatement[6] throughout income levels represent sufficient conditions to ensure that environmental quality improves with rising per capita income. However, this result does not hold anymore if the efficiency of abatement decreases throughout economic growth. In other words, even if the citizens are willing to pay proportionally more for the environmental protection as their income rises, the environmental quality will not improve if the cost of abating emissions also rises with income. Accordingly, Selden and Song's (1995) model shows that the extent to which increasing abatement costs offsets the demand effect associated with rising income depends of the pace of capital growth and the impact of that growth on pollution.

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 to consumption or to pollution abatement. If the economy is characterised by increasing returns to scale in pollution abatement process, i.e., 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 in the Andreoni and Levinson's (2001) setting.

The short overview of theoretical models giving rise to the Environmental Kuznets Curve points out that the shape of the relationship between abatement costs and income is of great importance for determining the pollution-income path. Abatement costs are likely to vary across countries and levels of income. The structural economic changes occurring throughout economic growths and technological developments may contribute to these differences. The development of environmental institutions may lead high-income economies toward 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 evolution of abatement costs across different levels of income or countries are rare. Intergovernmental Panel on Climate Change (IPCC, 2001) reviews national studies on CO_2 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 on theoretical models rather than on empirical studies (Chapman and Khanna, 2000). Abatement costs for air pollutants have been examined by Bluffstone (1997) for Lithuania and Hartman et al. (1994) for the USA. Dasgupta et al. (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

[6] I.e., if the reduction of one unit of emissions necessitates more and resources as income per capita rises.

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 has drawn much attention.

3. Estimating the Shadow Prices of Undesirable Outputs

In order to analyse evolution of the opportunity costs of CO_2 abatement with income, this paper reports empirical evidence based on a production model. Technology is modelled by means of directional output distance function. This technique allows us 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 CO_2 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 case – employ multiple inputs denoted by a vector $x = (x_1, x_2, \ldots, x_P) \in \Re_+^P$ to produce a vector of desirable outputs (goods, e.g., GDP or consumption) $y = (y_1, y_2, \ldots, y_Q) \in \Re_+^Q$ and a vector of undesirable outputs (bads, or pollution emissions) $b = (b_1, b_2, \ldots, b_R) \in \Re_+^R$. The technology may be described in a very general way via the output correspondence (or requirement) set (Färe and Lovell, 1985):

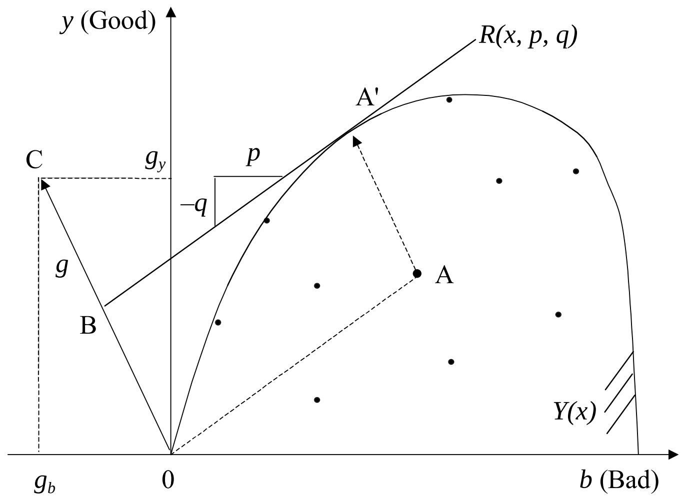
$$Y(x) = \{(y, b) \mid x \text{ can produce } (y, b)\}. \tag{1}$$

Following Chung et al. (1997), we impose standard assumptions on Y(x), namely, 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. For more details on these assumptions, see Appendix 1.

An example of production set Y(x) that satisfies these assumptions is reported in Figure 1. 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 et al. (1997) and Chambers et al. (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 Färe et al. (2001) and Lee et al. (2002). Denote the directional output vector by $g = (g_b; g_y)$, where $g_b = (g_{b1}, g_{b2}, \ldots, g_{bR}) \in \Re_-^R$ and $g_y = (g_{y1}, g_{y2}, \ldots, g_{yQ}) \in \Re_+^Q$. The associated directional output distance function is defined as:

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



Notes: 0A||BA', 0B||AA'
For country A, $D_o^A(x, y, b; g) = \beta = OB/OC$

Figure 2. Output correspondence set Y(x) and directional output distance function for a given input mix

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 far (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 Luenberger (1992), Chung et al. (1997) and Chambers et al. (1998), and hence will not be recalled in this paper.

According to Chambers et al. (1998), directional distance function fully characterises the technology, in the sense that

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

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

Chambers et al. (1998) and Färe et al. (2001) 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 $p = (p_1, p_2, \ldots, p_Q) \in \Re_+^Q$ is the price vector for desirable outputs and $q = (q_1, q_2, \ldots, q_R) \in \Re_-^R$ 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

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

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 et al., 1993). Finally, when the desirable output is measured directly in dollars, the relative shadow price q/p equals the absolute shadow price of CO_2 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 et al. (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 2. 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 CO_2 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 (CO_2). 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, CO_2 emissions, labour force, arable land and energy consumption have been collected in the World Development Indicators (WDI) database. Data on consumption come from the Penn World Table (PWT, mark 5.6).

To measure the CO_2 emissions, the WDI consider the pollution stemming from burning of fossil fuels and cement manufacturing. These comprise CO_2 emissions due to utilisation of solid, liquid, and gas fuels and gas flaring. Input "energy consumption" refers to primary

[7] This classification is based on the United Nations International Comparison Program (ICP): see Appendix 3.

energy, natural gas, solid fuels, and primary electricity. The energy obtained from all these sources is converted into oil equivalent. The arable land (in hectares) includes the land under temporary crops, temporary meadows for mowing or for pasture, land under market or kitchen gardens, and land temporarily fallow.[8] 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. Table 2 displays the correlation coefficients among inputs and outputs.

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

Table 2. Coefficients of correlation among inputs and outputs

Variables	CO_2	GDP	Consumpt.	Capital stock	Labour force	Energy consumpt.
GDP	0.94					
Consumption	0.98	0.99				
Capital stock	0.92	0.99	0.98			
Labour force	0.51	0.40	0.46	0.32		
Energy consumption	0.99	0.96	0.98	0.93	0.50	
Arable land	0.79	0.73	0.78	0.69	0.73	0.81

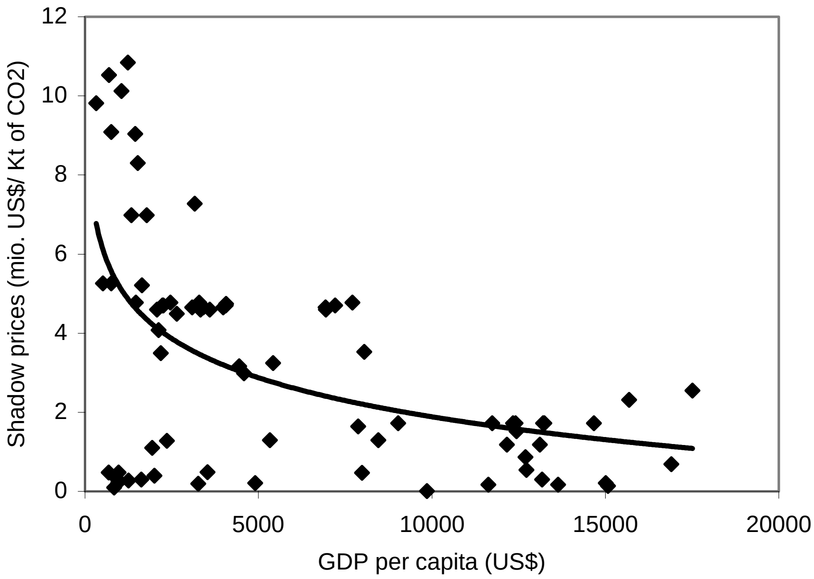
[8] According to the United Nations Food and Agriculture Organization's (FAO) definition of arable land, the double-cropped areas are counted once.

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 CO_2 emissions. The second part reports the "win-win" situations existing for some countries where the CO_2 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. Shadow prices of CO_2 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 CO_2 pollution had to be eliminated. Figure 3 depicts the negative relationship between shadow price estimates and desirable output. Figure 3(a) employs GDP per capita as a measure of desirable output whereas consumption per capita is used in Figure 3(b). Table 3 reports some descriptive statistics on the shadow prices by income group. More details regarding the estimated shadow prices per country are given in Appendix 4. The negative relationship between the income/consumption per capita and the marginal cost of CO_2 abatement was also assessed by means of OLS regressions reported in Appendix 5.



Panel (a)

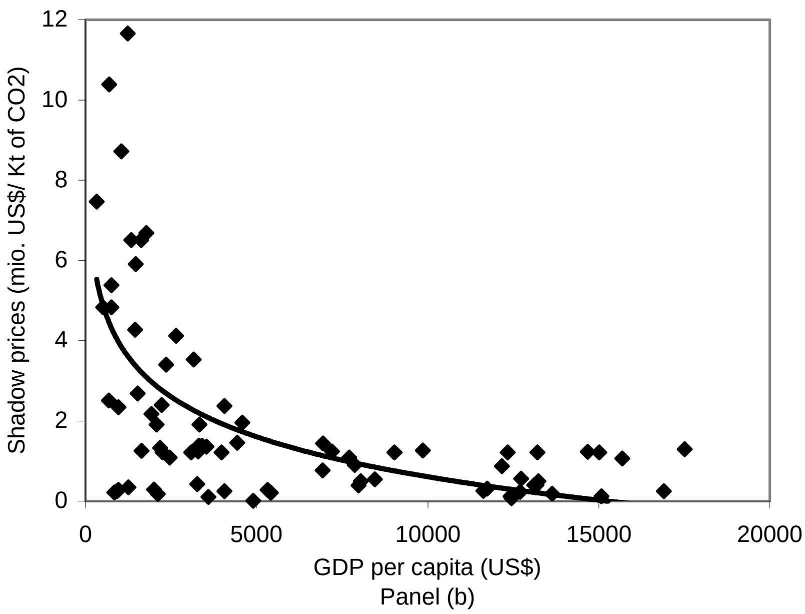


Figure 3. Shadow prices estimates vs. GDP per capita. Panel (a): GDP is used as a measure of desirable output. Panel (b): consumption is used as a measure of desirable output

Table 3. 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.

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. 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

[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.

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 data[10] come from the Penn World Table (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 (Figure 4).

Shadow prices for alternative directional vectors $g = (g_y, g_b)$ was also estimated. By doing so, the 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 CO_2 emissions and the countries' income level remains unchanged. Finally, shadow prices for alternative years (1980 and 1990) were estimated without changing this pattern.

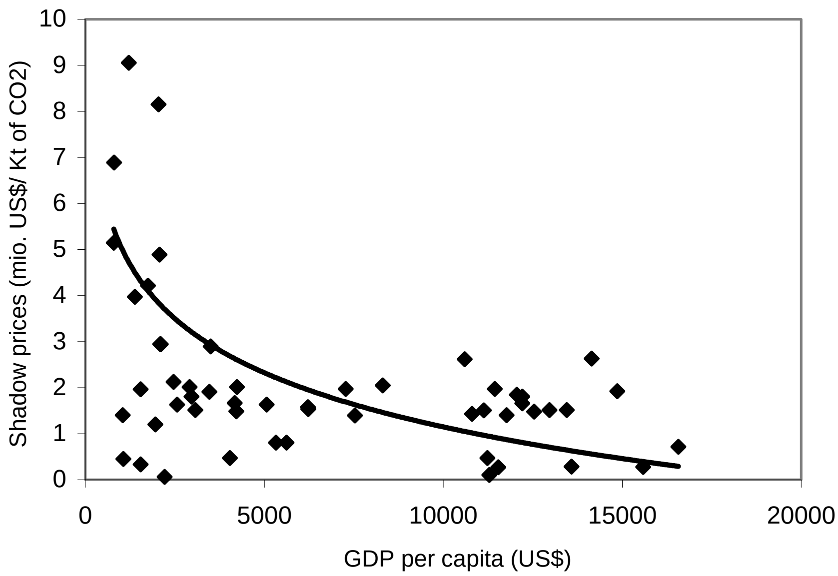


Figure 4. Shadow prices estimates vs. GDP per capita with alternative capital and GDP data (desirable output is GDP; 57 countries)

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 2. Economies with

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

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 sacrifying desirable output. The amount of CO_2 that could have been avoided without reducing the desirable output by country i (Δb_i) is computed according to the following formula (Chung et al., 1997):

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

where b_i is the observed quantity of CO_2 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 CO_2 emissions in the sample). Note that $(b_i - \beta_i g_b) = b_i^*$ equals the estimated minimum attainable level of CO_2 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 so important because the five outliers are responsible for a very large part of the CO_2 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 CO_2 emissions. Detailed results figure in Appendix 6.

The location of the zero-cost reductions does not follow a particular pattern across income levels, as depicted in Figure 5. The zero-cost reduction possibilities are however positively correlated with pollution intensity (ratio of CO_2 emissions to GDP), according to Figure 6. This result supports the hypothesis that the marginal abatement costs are low when pollution load is high (Pearce, 1977).

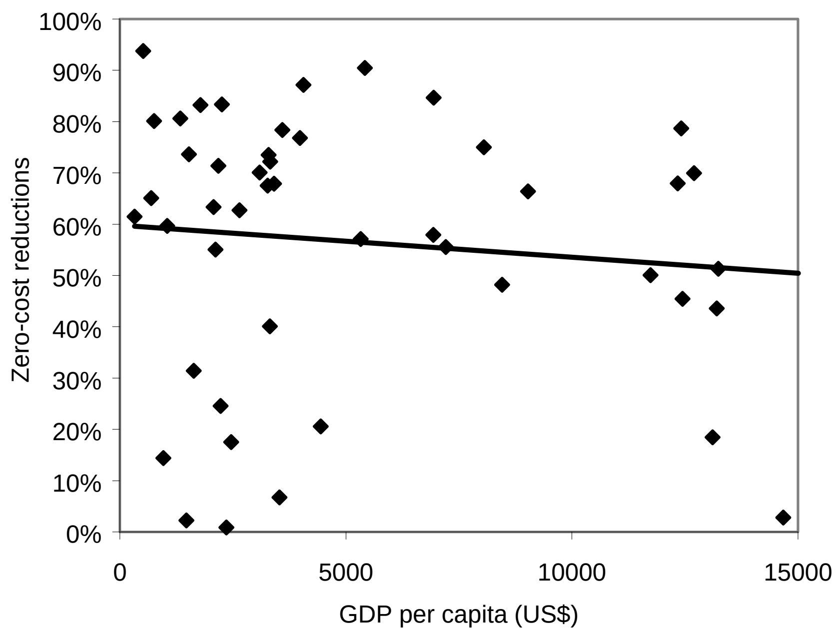


Figure 5. Zero-cost emission reductions (% of total national emissions) vs. GDP per capita

[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.

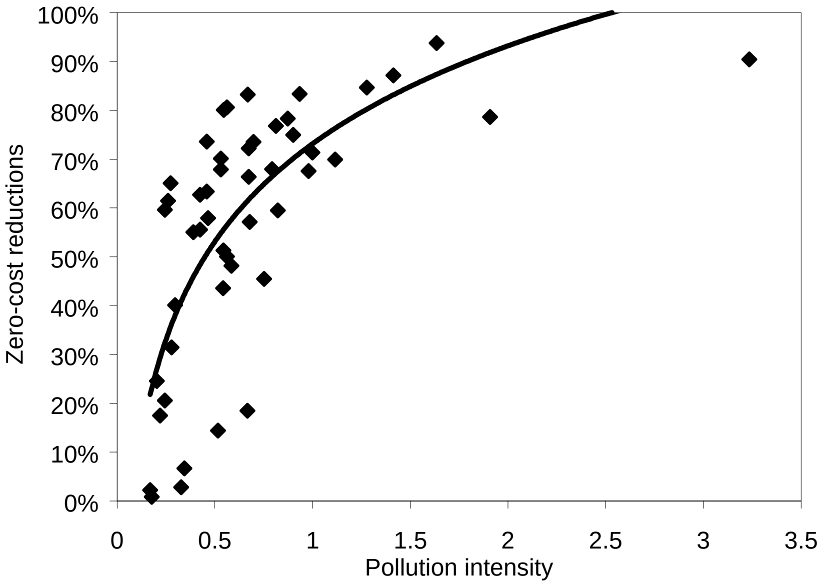


Figure 6. Zero-cost emission reductions (% of total national emissions) vs. pollution intensity

This results regarding the existence of zero-cost opportunities of CO_2 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. This uncertainty may reveal even greater if the production frontier is not static through time, but can move 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).

6. Discussion

This paper evaluates the economic burden that reduction of carbon dioxide emissions might generate, and relates the opportunity cost of CO_2 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 CO_2 abatement diminishes as the country's per capita GDP grows. The same relationship was found between the CO_2 abatement costs and per capita CO_2 emissions. This could be expected, because GDP per capita and CO_2 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.

Marginal opportunity cost of carbon dioxide abatement diminishing with per capita GDP constitutes an empirical finding which is in line with economic theory. Indeed, Baumol and Oates (1997) 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 computations of shadow prices for carbon dioxide confirm theoretical relationship between pollution emissions and development.

Marginal costs of CO_2 abatement decreasing with income, one could expect, *ceteris paribus*, to observe diminishing levels of CO_2 emissions in the high-income countries. Carbon dioxide abatement becoming more and more cheap 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 CO_2 emissions, but a monotonically increasing pattern of emissions with GDP per capita (Agras and Chapman, 1999; Perrings and Ansuategi, 2000). How this is possible? Carbon dioxide emissions might rise as development proceeds, because society might perceive no benefit in reducing CO_2 emissions. Explanations of no EKC for carbon dioxide may lay 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 emissions.

According to empirical findings in Section 5, 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 CO_2 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 CO_2 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 CO_2 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 CO_2 abatement costs and GDP per capita. It is possible to include information on technical inefficiencies in the estimation of shadow prices (Lee et al., 2002), and this approach constitutes an interesting topic for future research.

Positive correlation between the estimated amounts of zero-cost CO_2 reductions and pollution intensities (which equals the ratio of CO_2 emissions to GDP) is in line with theoretical arguments. Indeed, Pearce (1977) 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). Indeed, 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 abating CO_2 measured in terms of consumption or GDP forgone (i.e., it is assumed that to reduce pollution, it is necessary to reduce the production of desirable outputs). These are different from the costs calculated by bottom-up and top-down models, according to IPCC (2001). According to IPCC's (2001), little correlation exists between the amount of carbon tax necessary to reach a certain emission target, and the GDP loss faced by the country. Moreover, as shown by Coppel (1993), a global carbon tax imposed identically to all countries would result in a disproportionate burden on developing economies. Next, usual abatement costing studies refer to the reduction of *future* emissions according to a business-as-usual scenario, while our measure rests on *current* emissions. This constitutes the second major difference between our results and the IPCC's (2001) estimates. Finally, 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. 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 the existence of a causality relationship between the growth of income per capita and the decay of marginal pollution abatement costs. All what is found is a negative correlation. The existence of correlation (not causality) relationship does not rule out the possibility that for some countries, abatement costs do not fall as development proceeds. Hence, our findings – drawn from cross-section data analysis – might be impossible to generalise to time-series setting. In other words, developing countries might be so different, as to their technological regimes, from the developed countries, 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 CO_2 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, the quality of environmental data for low-income economies is sometimes uncertain. Shafik (1994) and Lieb (2002) warn that the usage of environmental pollution data might be

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[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.

problematic for cross-country comparisons, because these data may be flawed by the differences in definitions, inaccuracies, and might come from unrepresentative measurement sites. This concern has been largely ignored in the empirical literature. However, as mentioned by Roberts and Grimes (1997), carbon dioxide data are the best of any pollutant, regarding both their coverage and adequacy.

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, 1995). Moreover, production frontiers might be influenced by some 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 CO_2 emissions, the issue of exogenous conditions needs further investigation.[13]

7. Conclusions

The purpose of this paper was to advance an evidence-based approach to understand the impact if income growth on the marginal cost of pollution abatement. We concentrated on the emissions of carbon dioxide, and empirically evaluated the marginal abatement costs of CO_2 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 CO_2 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 in 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 CO_2 emissions. Ever increasing CO_2 emissions observed throughout economic growth are *not* explained by growing abatement costs of carbon dioxide, because these costs decrease as development proceeds. They might be rather due to a low society's demand for CO_2 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 which often appears in the literature (IPCC, 2001). Furthermore, the amount of CO_2 emissions that could

[13] Especially when we see (in Appendix 6) that zero-cost pollution reductions might exceed 80% of countries' total CO_2 emissions, which is obviously implied by very large amounts of inefficiencies! The existence of so large inefficiencies might be due to the lack of accounting for the influence of exogenous variables affecting the production processes.

be abated a zero cost (expressed as a percentage of total national emissions) is larger in countries whose pollution intensities are high. It is well known that economies characterised by high pollution intensities are often those that attained a high degree of economic development.

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 abatement costs 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 growth. 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 et al. (2002), is also a promising direction for further research.

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Appendix 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: $(0, 0) \in Y(x)\ \forall x \in \Re_+^P$. 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 $x \in \Re_+^P$, 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.

Appendix 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:

$$D_o(x, y, b; g) = \max \beta \tag{A1}$$

subject to

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

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

$$\sum_{i=1}^{N} z_i x_{i,p} \leq x_{A,p} \quad p = 1,\dots,P,$$

$$\delta \geq 1,$$

$$\beta \quad \text{is} \quad \text{free},$$

$$z_i \geq 0 \quad \forall i = 1,\dots,N$$

The parameter β, or the technical efficiency score, is free but implicitly constrained to be non-negative. It 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,…, N are called intensity variables. The non-negativity constraints on these variables force the technology to exhibit the constant returns to scale (CRS). The variable returns to scale (VRS) are obtained by adding to the above LP the constraint $\sum_{i=1}^{N} z_i = 1$, and the non-increasing (non-decreasing) returns to scale (NIRS and NDRS, respectively) are obtained by setting the sum of intensity variables z_i to be lower (greater) or equal than one.

The inequalities in the constraints for inputs x make them freely disposable, and the same holds 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). Under constant returns to scale, δ may be set equal to one, thus making the mathematical programming problem linear. The strict equality on the bads constraints along with the scaling possibilities afforded under constant returns to scale yields weak disposability of (y, b). Under variable, non-increasing or non-decreasing returns to scale, (A1) may be easily transformed into a linear programming problem by defining the new intensity variables $\gamma_i = z_i/\delta$ for i = 1,…, N. In what follows, we assume variable returns to scale, i.e., the least restrictive hypothesis. 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.[14]

Appendix 3. Countries included in the sample

The countries analysed in this paper belong to four income groups. These groups have been 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:

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.

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.

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.

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.

[14] 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 $D_o(x, y, b; g)$.

Appendix 4. Shadow price estimates and efficiency scores

Table A.1. Shadow price estimates and efficiency scores (desirable output: GDP, year 1985)

Country	Income group	Efficiency score	# Dominated units	Shadow price bad	Shadow price good	Ratio of shadow prices
Algeria	2	0.3084	0	0.005670794	-0.001218381	4.654368653
Argentina	3	0.3205	0	0.005670794	-0.001218381	4.654368653
Australia	4	0.8845	0	0.005670794	-0.006537906	0.867371702
Austria	4	0.1336	0	0.005670794	-0.003297279	1.719840583
Bangladesh	1	0	7	0.005670794	-0.00107857	5.257698928
Belgium	4	0	1	0.005670794	-0.033106594	0.17128897
Bolivia	2	0.0172	0	0.005670794	-0.000683295	8.299192659
Brazil	3	0	2	0.005670794	-0.001901792	2.981816429
Cameroon	1	0	0	0.005670794	-0.018942043	0.299376071
Canada	4	0	0	0.005670794	-0.04184105	0.135531837
Chile	3	0.0839	0	0.005670794	-0.001218381	4.654368653
China	2	0	0	0.005670794	-0.058005046	0.097763811
Colombia	2	0	38	0.005670794	-0.001187833	4.774068025
Congo, Dem. Rep.	1	0	24	0.005670794	-0.000523185	10.8389844
Costa Rica	3	0	5	0.005670794	-0.00119555	4.743251658
Cote d'Ivoire	1	0.0339	0	0.005670794	-0.000812085	6.983001929
Cyprus	4	0	1	0.005670794	-0.003445769	1.645726736
Denmark	4	0.2132	0	0.005670794	-0.026951363	0.210408442
Dominican Republic	2	0.0257	0	0.005670794	-0.001262456	4.491873694
Ecuador	2	0.0907	0	0.005670794	-0.001205865	4.702677346
Egypt, Arab Rep.	2	0	2	0.005670794	-0.014230138	0.398505919
El Salvador	2	0.0001	0	0.005670794	-0.004433567	1.279059234
Finland	4	0.1846	0	0.005670794	-0.003297279	1.719840583
France	4	0	0	0.005670794	-0.010453063	0.542500736
Germany	4	0.712	0	0.005670794	-0.004810305	1.178884566
Ghana	1	0.0109	0	0.005670794	-0.000560068	10.12519482
Greece	4	0.2271	0	0.005670794	-0.003297279	1.719840583
Guatemala	2	0.0049	0	0.005670794	-0.001205865	4.702677346
Haiti	1	0	22	0.005670794	-0.000627206	9.041358972
Honduras	2	0.0034	0	0.005670794	-0.001087656	5.213774401
Iceland	4	0	14	0.005670794	-0.002448142	2.316366875
India	1	0	0	0.005670794	-0.017305322	0.327690779
Indonesia	1	0	1	0.005670794	-0.020786581	0.272810342
Iran, Islamic Rep.	2	0.6558	0	0.005670794	-0.001234291	4.594374784
Ireland	4	0.1091	0	0.005670794	-0.001608094	3.526406708
Israel	4	0	0	0.005670794	-0.548628815	0.010336304
Italy	4	0	2	0.005670794	-0.004810305	1.178884566
Jamaica	2	0.0204	0	0.005670794	-0.001621619	3.496996368
Japan	4	0	4	0.005670794	-0.018926703	0.299618715
Jordan	2	0.0324	0	0.005670794	-0.028712147	0.197505058
Kenya	1	0.0139	0	0.005670794	-0.000538499	10.5307418
Korea, Rep.	4	0	0	0.005670794	-0.027352735	0.207320923
Kuwait	4	0	0	0.005670794	-0.012089887	0.469052701
Luxembourg	4	0.0388	0	0.005670794	-0.003297279	1.719840583
Malaysia	3	0.1499	0	0.005670794	-0.001187833	4.774068025
Mexico	3	0.8823	0	0.005670794	-0.004385639	1.293037093
Morocco	2	0.0557	0	0.005670794	-0.001391847	4.074294678
Mozambique	1	0.004	0	0.005670794	-0.000577546	9.818780757
Netherlands	4	0.3491	0	0.005670794	-0.003722927	1.52320873

New Zealand	4	0.0613	0	0.005670794	-0.003297279	1.719840583
Nicaragua	1	0	2	0.005670794	-0.005161997	1.098566002
Nigeria	1	0.3714	0	0.005670794	-0.00107857	5.257698928
Norway	4	0.0032	0	0.005670794	-0.003297279	1.719840583
Pakistan	1	0.0384	0	0.005670794	-0.025291829	0.22421448
Panama	3	0.001	0	0.005670794	-0.011654201	0.486587988
Paraguay	2	0	17	0.005670794	-0.000779968	7.270543589
Peru	2	0.0435	0	0.005670794	-0.001205865	4.702677346
Philippines	2	0.0292	0	0.005670794	-0.001187833	4.774068025
Portugal	4	0.0964	0	0.005670794	-0.001205865	4.702677346
Senegal	1	0	0	0.005670794	-0.011851882	0.478472063
South Africa	2	1.3321	0	0.005670794	-0.001234291	4.594374784
Spain	4	0.5183	0	0.005670794	-0.004385639	1.293037093
Sri Lanka	2	0.0005	0	0.005670794	-0.001187833	4.774068025
Sudan	1	0	0	0.005670794	-0.011791521	0.480921373
Sweden	4	0.175	0	0.005670794	-0.003297279	1.719840583
Switzerland	4	0	10	0.005670794	-0.002221851	2.552284061
Thailand	2	0.1747	0	0.005670794	-0.001234291	4.594374784
Trinidad and Tobago	3	0.1059	0	0.005670794	-0.001745692	3.248450309
Tunisia	2	0.0474	0	0.005670794	-0.001218381	4.654368653
Turkey	2	0.4616	0	0.005670794	-0.001234291	4.594374784
United Kingdom	4	0	0	0.005670794	-0.032769654	0.173050172
United States	4	0	0	0.005670794	-0.008264649	0.686150632
Uruguay	3	0.0038	0	0.005670794	-0.001790366	3.167394592
Venezuela, RB	3	0.486	0	0.005670794	-0.001205865	4.702677346
Zambia	1	0.0125	0	0.005670794	-0.000624066	9.086850109
Zimbabwe	1	0.0484	0	0.005670794	-0.000812085	6.983001929

Table A.2. Shadow price estimates and efficiency scores (desirable output: consumption, year 1985)

Country	Income group	Efficiency score	# Dominated units	Shadow price bad	Shadow price good	Ratio of shadow prices
Algeria	2	0.3208	0	0.005670794	-0.004667061	1.21506757
Argentina	3	0.1562	0	0.005670794	-0.007402808	0.76603292
Australia	4	0.4816	0	0.005670794	-0.024236943	0.23397316
Austria	4	0.1195	0	0.005670794	-0.004667061	1.21506757
Bangladesh	1	0	5	0.005670794	-0.00117307	4.83414816
Belgium	4	0	0	0.005670794	-0.030622228	0.18518555
Bolivia	2	0.0119	0	0.005670794	-0.002111725	2.68538479
Brazil	3	0	16	0.005670794	-0.002904588	1.95235764
Cameroon	1	0.0279	0	0.005670794	-0.000871386	6.50778818
Canada	4	0	0	0.005670794	-0.04652908	0.12187635
Chile	3	0.0791	0	0.005670794	-0.004109731	1.37984576
China	2	0	1	0.005670794	-0.025924474	0.21874289
Colombia	2	0.0885	0	0.005670794	-0.005234748	1.08329852
Congo, Dem. Rep.	1	0	14	0.005670794	-0.000486646	11.6528027
Costa Rica	3	0	3	0.005670794	-0.002391003	2.37172201
Cote d'Ivoire	1	0.0331	0	0.005670794	-0.000871386	6.50778818
Cyprus	4	0	1	0.005670794	-0.006305945	0.89927742
Denmark	4	0.2311	0	0.005670794	-0.004681562	1.21130378
Dominican Republic	2	0.0279	0	0.005670794	-0.001376881	4.11858058
Ecuador	2	0.0802	0	0.005670794	-0.004667061	1.21506757
Egypt, Arab Rep.	2	0	0	0.005670794	-0.019685904	0.2880637
El Salvador	2	0.001	0	0.005670794	-0.001668794	3.39813912

Finland	4	0.1661	0	0.005670794	-0.004681562	1.21130378
France	4	0	5	0.005670794	-0.010100604	0.5614312
Germany	4	0.4768	0	0.005670794	-0.014322331	0.39594073
Ghana	1	0.0132	0	0.005670794	-0.000650184	8.72182414
Greece	4	0.197	0	0.005670794	-0.004667061	1.21506757
Guatemala	2	0	15	0.005670794	-0.002369436	2.39330948
Haiti	1	0	11	0.005670794	-0.001327634	4.27135333
Honduras	2	0.0008	0	0.005670794	-0.004510231	1.25731804
Iceland	4	0	11	0.005670794	-0.005341148	1.06171818
India	1	0.0355	0	0.005670794	-0.022607032	0.25084206
Indonesia	1	0	0	0.005670794	-0.016662466	0.34033343
Iran, Islamic Rep.	2	0	0	0.005670794	-0.055020046	0.10306779
Ireland	4	0.0837	0	0.005670794	-0.011438709	0.49575475
Israel	4	0.0926	0	0.005670794	-0.004505293	1.25869613
Italy	4	0	3	0.005670794	-0.006535535	0.86768631
Jamaica	2	0.0169	0	0.005670794	-0.004270587	1.32787224
Japan	4	0	1	0.005670794	-0.014271814	0.39734224
Jordan	2	0	1	0.005670794	-0.013483299	0.42057914
Kenya	1	0.0161	0	0.005670794	-0.000545946	10.3870901
Korea, Rep.	4	0	0	0.005670794	-0.76160798	0.00744582
Kuwait	4	0	0	0.005670794	-0.014600878	0.38838722
Luxembourg	4	0	0	0.005670794	-0.046200588	0.1227429
Malaysia	3	0.1285	0	0.005670794	-0.004591894	1.23495768
Mexico	3	0	6	0.005670794	-0.020228266	0.28034011
Morocco	2	0	0	0.005670794	-0.032893842	0.17239684
Mozambique	1	0.001	0	0.005670794	-0.000759791	7.46361991
Netherlands	4	0	0	0.005670794	-0.082454796	0.06877458
New Zealand	4	0.0054	0	0.005670794	-0.018198642	0.31160535
Nicaragua	1	0.0034	0	0.005670794	-0.002610901	2.17196844
Nigeria	1	0.3547	0	0.005670794	-0.00117307	4.83414816
Norway	4	0.0122	0	0.005670794	-0.004626553	1.22570618
Pakistan	1	0	0	0.005670794	-0.020072292	0.28251852
Panama	3	0	0	0.005670794	-0.004178134	1.35725537
Paraguay	2	0	6	0.005670794	-0.001608196	3.52618259
Peru	2	0.0451	0	0.005670794	-0.004109731	1.37984576
Philippines	2	0.0684	0	0.005670794	-0.005234748	1.08329852
Portugal	4	0.0966	0	0.005670794	-0.004591894	1.23495768
Senegal	1	0	3	0.005670794	-0.002421762	2.34159812
South Africa	2	1.4645	0	0.005670794	-0.003941628	1.43869339
Spain	4	0.2307	0	0.005670794	-0.010520751	0.53901042
Sri Lanka	2	0	14	0.005670794	-0.000960457	5.90426655
Sudan	1	0.0065	0	0.005670794	-0.002262325	2.50662285
Sweden	4	0.0923	0	0.005670794	-0.011438709	0.49575475
Switzerland	4	0	20	0.005670794	-0.004389738	1.29182979
Thailand	2	0.1619	0	0.005670794	-0.002967163	1.91118364
Trinidad and Tobago	3	0	0	0.005670794	-0.027725308	0.20453494
Tunisia	2	0.0416	0	0.005670794	-0.004681562	1.21130378
Turkey	2	0.4498	0	0.005670794	-0.002967163	1.91118364
United Kingdom	4	0	1	0.005670794	-0.022298193	0.25431632
United States	4	0	2	0.005670794	-0.022556136	0.25140806
Uruguay	3	0	4	0.005670794	-0.003904463	1.45238762
Venezuela, RB	3	0.1621	0	0.005670794	-0.022778367	0.24895527
Zambia	1	0.0124	0	0.005670794	-0.001053224	5.38422602
Zimbabwe	1	0.0527	0	0.005670794	-0.000849031	6.67914041

Appendix 5. Regressions of shadow prices estimates

Regression for the shadow prices estimated by using GDP per capita as a measure of desirable output:

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.

Regression for the shadow prices estimated by using consumption per capita as a measure of desirable output:

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.

Appendix 6. Zero-Cost Abatement Opportunities

Countries with existing zero-cost CO_2 abatement opportunities:

Country	Kt of CO_2	% of total emissions	Country	Kt of CO_2	% of total emissions
Algeria	54384	77%	Morocco	9822	55%
Argentina	56518	58%	Mozambique	705	61%
Australia	155975	70%	Netherlands	61561	45%
Austria	23559	44%	New Zealand	10810	50%
Bolivia	3033	74%	Nigeria	65493	94%
Chile	14795	68%	Norway	564	3%
Cote d'Ivoire	5978	81%	Pakistan	6772	14%
Denmark	37596	60%	Panama	176	7%
Dominican Republic	4532	63%	Peru	7671	40%
Ecuador	15994	83%	Philippines	5149	18%
El Salvador	18	1%	Portugal	16999	56%
Finland	32553	68%	South Africa	234905	85%
Germany	125556	18%	Spain	91398	48%
Ghana	1922	60%	Sri Lanka	88	2%
Greece	40047	66%	Sweden	30860	51%
Guatemala	864	25%	Thailand	30807	63%
Honduras	600	31%	Trinidad and Tobago	18675	90%
Iran, Islamic Rep.	115645	78%	Tunisia	8359	70%
Ireland	19239	75%	Turkey	81400	72%
Jamaica	3597	71%	Uruguay	670	21%
Jordan	5713	68%	Venezuela, RB	85702	87%
Kenya	2451	65%	Zambia	2204	80%
Luxembourg	6842	79%	Zimbabwe	8535	83%
Malaysia	26434	73%			
Mexico	155587	57%	**TOTAL**	**1688758**	**13%**

Countries with no zero-cost CO_2 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.