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Estimating Shadow Prices of Pollution in Selected OECD Countries

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This paper has been authorised for publication by Simon Upton, Director, Environment Directorate.

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FOREWORD

The objective of this paper is to estimate time variant shadow prices for CO_2, SO_x, NO_x and PM_{10} in 19 OECD countries over the period 1990-2008 relying on an output distance function approach. Shadow prices for pollutants are found to vary widely across countries, depending on national environmental regulations, the use of inefficient abatement technologies and the structure of the economy. All countries but Korea experienced a decline in CO_2 and NO_x prices over the period 1990-2008, with the bulk of the decrease occurring since 2000. This suggests that most OECD countries have strengthened their regulatory framework and encouraged the adoption of clean technologies since the 2000s. Estimates of shadow prices of PM_{10} appear to be extremely variable across countries. Contrary to what is observed for CO_2 and NOx, steep declines have occurred in both 1990-2000 and 2000-2008 sub-periods. The empirical work undertaken in this paper could easily be replicated to other countries, and is relatively parsimonious in terms of data.

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EXECUTIVE SUMMARY

Now that pollution is reaching worrisome levels in some countries and at the global level, there is a growing consensus that it needs to be explicitly considered as a by-product of the production process and incorporated in economic decisions. But this is not easy in the absence of markets and observable prices. Shadow prices of pollution, the opportunity cost of abating pollution in the form of reduced output, have to be estimated using specific techniques and serve several purposes. It's a signal firms have to take into consideration when they decide upon their investment decisions. Shadow prices can also inform policymakers when they set policies. They can be used to assess policy *ex ante* by comparing the marginal benefits of environment policies with the cost they involve for private firms. These prices can be seen as benchmark for allowance price in emission market-based schemes or can be useful in designing optimal environmental tax schemes. The indicator can also be used *ex post* and can be considered as a policy indicator of pollution regulation and compliance to these regulations. More generally such prices are used each time there is a need to value pollution.

The objective of this paper is to estimate country-specific time variant shadow prices for pollution in 19 OECD countries over the period 1990-2008. The approach is based on an output distance function that is applied to four types of gas emissions: CO_2, SO_x, NO_x and PM_{10}. The empirical work undertaken in this paper could easily be replicated to other countries and is relatively parsimonious in terms of data.

Resulting shadow prices summarise multi-dimensional regulations into one measure of costs, though they are also likely to account for other factors than solely regulatory stringency (Brunel and Levinson, 2013). The estimation also reflects the structure of the economy and can be undertaken over time across countries, industries and pollutants. The drawback is that shadow prices depend on the functional form chosen for the output distance function and on the set of other inputs incorporated in the production function. More importantly, shadow prices in this context can be understood as the marginal cost for companies to freely dispose of waste generated in the production process. It is a narrow definition and, as such, shadow prices are likely to differ markedly from abatement costs for the society as a whole.

Empirical results point to the following conclusions:

- Shadow prices for pollutants are found to vary widely across countries, depending on national environmental regulations, the use of inefficient abatement technologies and the structure of the economy. Low shadow prices (in absolute terms) would signal less stringent regulations or weak compliance towards existing regulation as the technology used remains relatively inefficient.

- CO_2 shadow prices are estimated to be the lowest (in absolute terms) in Australia and Canada and the highest in Switzerland. All countries but Korea experienced a decline in prices over the period 1990-2008, with the bulk of the decrease occurring since 2000. This suggests that most OECD countries have strengthened their regulatory framework and encouraged the adoption of clean technologies since the 2000s.

- NOx shadow prices are estimated to be much lower than CO_2 prices, reflecting a much higher output-over-emissions ratio. Switzerland and to a lesser extent Japan, the Netherlands and Sweden displayed lower shadow prices than average. All countries experienced a marked fall over time, with the most significant declines being observed in the United Kingdom, the Netherlands and Ireland.

- The SO_x elasticity to good output is not estimated to be significantly different from zero, precluding the estimation of shadow prices for this gas.

- Estimates of shadow prices of PM_{10} appear to be extremely variable across countries. Contrary to what is observed for CO_2 and NOx, steep declines have occurred in both 1990-2000 and 2000-2008 sub-periods and were particularly marked in Australia and Korea.

- The analysis is subject to a number of caveats. First, it has been undertaken at a very aggregate level and can hide wide disparities across sectors. In this regard, undertaking a similar exercise at the sectoral level is likely to be very informative. In addition, the estimation method could be refined to better account for country heterogeneity but this may require changing the framework to be able to test the significance of the pollutant-to-output elasticities. Finally, it would be important to get estimates of the uncertainties surrounding shadow price estimates, for instance through monte-carlo simulations.

INTRODUCTION

There is now a wide recognition that air pollution is one undesirable by-product of production processes that can have deleterious effect on productivity and long-term production. Such effects are nonetheless usually not fully accounted for in economic policy, given the difficulty to value the opportunity cost of abating pollution either for the society as a whole or for producers. “Shadow prices of undesirable outputs” measure such cost but need to be derived indirectly, in a context where market prices are typically unobservable.

The objective of this paper is to estimate country-specific time variant shadow prices for pollution in 19 OECD countries over the period 1990-2008. The approach is based on an output distance function, the distance between existing technologies and the frontier of efficiency, and relies on mainstream theoretical literature. Resulting shadow prices summarise multi-dimensional regulations into one measure of costs, though they are also likely to account for other factors than solely regulatory stringency (Brunel and Levinson, 2013). The estimation also reflects the structure of the economy and can be undertaken over time across countries, industries and pollutant. The drawback is that shadow prices depend on the functional form chosen for the output distance function and on the set of other inputs incorporated in the production function. More importantly, shadow prices in this context can be understood as the marginal cost for companies to freely dispose of wastes generated in the production process. It is a narrow definition and, as such, shadow prices are likely to differ markedly from abatement costs for the society as a whole.

The paper unfolds as follows. A first section highlights the usefulness of estimating shadow prices of pollution but also the difficulties associated with such an exercise. A second section presents the theoretical framework used to derive shadow prices. A third section describes the empirical approach. Resulting empirical estimates for 19 OECD countries are subsequently discussed in a fourth section. A last section concludes.

1. LITERATURE REVIEW

Shadow prices of pollution contain useful information…

Shadow prices provide an estimate of pollutants' value and can inform both economic and policy decisions.

At the firm level, information on the marginal abatement costs of undesirable by-product of the production process allows undertaking project appraisal through cost-benefit analysis. Such information can then be incorporated in firms' investment decisions.

An accurate estimation of shadow prices can also help policymakers in setting environmental regulatory policy:

- They can be used to assess policy *ex ante* by comparing the marginal benefits of environment policies with the cost they involve for private firms.
- They also bring useful information to ensure economic instruments in the short term are consistent with long-term objectives. Shadow prices can be used as a reference value of allowance price in emission market-based schemes, when such schemes are put in place. Regulators can also view shadow prices as a benchmark to set penalty rates for emissions of various pollutants and in allocating the resources for pollution control among plants. For instance, shadow prices can be useful in designing optimal environmental tax schemes.
- Finally, shadow prices could be useful in long-term analysis as they help "greening GDP", *i.e.* correcting GDP and its components for the value of environmental pollution. For instance, they are required to adapt traditional productivity indexes and correct for the intensity of waste production.

… but are notoriously difficult to estimate

As shadow prices of undesirable outputs are not observable, specific methods have been used to estimate them. In this section, the focus is on one strand of the literature that is the most relevant to the approach adopted in this paper: the estimation of shadow prices using distance functions and either stochastic or deterministic methods. The merits and limits associated with the different methods are reviewed. Subsequently, the sources of the very large variability of existing shadow price estimates in the literature are discussed.

The computation of shadow prices has often relied on an output distance function setting

Environmental externalities can be valued using various techniques, but all of them present some important limits. For instance, the contingent valuation method involves directly asking people, in a survey, to state their willingness to pay for pollution reduction. Such method is subject to drawbacks related to the representativeness of the sample, limited choice of pollutants and aggregation issues (Salnykov and Zelenyuk, 2005). Other authors have estimated shadow prices through the estimation of a system of Cobb-Douglas functions, but this approach makes a relatively strong assumption on the specification of the production function and is difficult to use for a group of heterogeneous countries.

An important strand of the literature has derived shadow prices from the estimation of output distance function. Generally studies use a multi-output setting in which production yields some outputs that are desirable and other that are not and may not be freely disposable. They use the duality between the output distance function and the revenue function to derive shadow prices (Shephard, 1970). Thanks to this relationship and the maximization of the revenue function over quantities, shadow prices of pollution can be expressed as a function of the price of desirable output, the ratio of output over emissions and the elasticity of bad-output to good output at the frontier of efficiency (see below for a formal derivation).

As an output distance function cannot be directly estimated (because the distance/frontier is not observable), both deterministic and stochastic methods have been used to derive empirical estimates of shadow prices.

Boyd *et al.* (1996) and Lee *et al.* (2002) rely on a Data Envelopment Analysis (DEA) framework, a deterministic method that does not incorporate statistical noise. Estimation results are, however, relatively sensitive to outliers. Moreover, the observations of the production units need to be observed without error and the production model specified without omitting any inputs or outputs. Other more general methods such as Convex Nonparametric Least Squares (CNLS) have been developed to address these limits (Kuosmanen, 2006). Such an approach can nevertheless lead to non-unique solutions, given the existence of multiple solutions in linear programming (Salnykov and Zelenyuk, 2005).

Alternatively, a number of papers have opted for a stochastic model. A parametric method, which is more convenient to differentiate the distance function with respect to outputs and derive shadow prices, was first developed by Aigner and Chu (1968) and applied to output distance function by Färe *et al.* (1993). Most papers parametrise the output distance function by taking a translog functional form or a quadratic directional output distance function (Coggins and Swinton, 1996; Färe *et al.*, 2005; Murty and Kumar, 2002).

Parametric functions are often estimated with a Stochastic Frontier Analysis SFA (Murty and Kumar, 2002; Färe *et al.*, 2005; Cuesta *et al.*, 2009). This is the technique adopted in this paper. While such an approach can be biased if the functional form is misspecified, it has the advantage of requiring only a limited quantity of data. Compared to the DEA the estimated parameters are unlikely to suffer from being deterministic and sample biased (see Merk and Dang (2012) for a discussion). SFA also differs from the estimation of a common production function across countries at the sample mean using OLS, as it identifies and estimates the best existing production function (*i.e.* frontier of efficiency) within the sample of observations. As such, this technique allows deriving efficiency scores for individual countries/plants producing with their own technology. In this paper, inefficiency is assumed to vary over time and to follow a Normal-Truncated Normal distribution in line with Battese and Coelli (1995). Belotti *et al.* (2012) discuss the time issues at length.

Variability in existing estimates reflects difference in scope and in methodology

Estimates of shadow prices vary markedly across studies (Table 1), though confidence intervals are not necessarily reported so that it is difficult to assess whether reported differences are always statistically significant. In addition, most estimates are not strictly comparable. Indeed, shadow prices are often not expressed in the same unit or over the same period. Finally, studies also focus on a different geographical or sectoral scope. Most of the studies have looked at specific sectors, usually the coal or electric sectors which are emission-intensive. Qi *et al.* (2004) are amongst the few studies that compute economy-wide shadow prices for a number of air pollutants on 44 countries. Salnykov and Zelenyuk (2005) also computed shadow prices for CO_2, SO_2 and NOx for 15 countries including some OECD countries and China. In addition to differences in the coverage, Färe *et al.* (2005) and Salnykov and Zelenyuk (2005) show that shadow price estimates can also vary widely depending on the estimation method used.

Table 1. Selected estimates from the economic literature

Study	**Scope**	**Methodology**	**Shadow price (sample average)**	**Shadow price (2005 USD PPP/ton)**
CO_2				
Keilbach (1995)	Germany 1966-1990 Manufacturing industry	System of Cobb Douglas production functions	-182 DM/ton	-180.5
Qi *et al.* (2004)	44 countries 1980-2000	Distance function combining parametric and non parametric approach	-251 in 1995 $/ton	-308.5
Maradan and Vassiliev (2005)	76 developed and developing countries, 1985	Output distance function and linear programming	Between -0.01 to -10.83 $/tons, -1.16 on average for high-income countries	Between -0.01 to -10.83
Salnykov and Zelenyuk (2005)	96 countries, 1995	Output distance function, parametric and non parametric	Between -133.85 to -478.4 $/tons depending on the method	Between -133.85 to -478.4
Resek and Campbell (2007)	United States, 260 coal power plants, 1998	Output distance function	-18 to -21 $/tons depending on the method	-18 to -21
Australian Productivity Commission (2011)	Electricity sector in 6 OECD countries, 2010	Calculation of the estimated cost of policy compliance and estimates of abatement quantities	-43/-50 A$/tons in the US, -137/-175 in Germany, -156/-287 in Japan, -225/-401 in Korea, -44/-99 in Australia and -8/-10 in New Zealand	Between -6 and -218
SOx/SO_2				
Turner (1995)	US electric utility industry	DEA	-826 $/tons	-826
Coggins and Swinton (1996)	US –Winscosin, 1990-92	Translog, deterministic	-292.70 $/tons	-292.70
Keilbach (1995)	Germany, 1990 Manufacturing industry	System of Cobb Douglas production function	-18 DM/kg	-18.1
Boyd *et al.* (1996)	US coal plants, 1989	DEA	-1703 $/tons	-1703
Swinton (1998)	Winsconsin, Illinois and Minnesota coal burning electric plants	Output distance function	Between -4.08 and -4669 constant 1992 $/tons	Between -5.35 and -5991.9
Lee *et al.* (2002)	Korea electric power industry, 1990-1995	DEA, Non parametric directional distance function (account for inefficiency)	-3107 $/ton	-3107
Qi *et al.* (2004)	44 countries,	Distance function	-331 in 1995 $/ton	-406.8

	1980-2000	combining parametric and non parametric approach		
Färe *et al.* (2005)	US electric utilities in 1993 and 1997	Directional distance function Quadratic, deterministic Quadratic, composite	-1117/ -1974 $/ton -76/-142 $/ton	Between -76 and -1974
Salnykov and Zelenyuk (2005)	96 countries, 1995	Output distance function, parametric and non parametric	Between -868.78 and -34130 $/ton depending on the method	Between -868.78 and-34130
Resek and Campbell (2007)	United States, 260 coal power plants, 1998	Output distance function	between-134 and -470 $/tons depending on the method	Between -134 and-470
Mekaroonreung and Johnson (2012)	United States coal power plants, 2000-2008	Stochastic semi-non parametric envelopment of data Composite Deterministic	Between -126 and -860 $/tons And between -509 and -2020 $/ton	Between -126 and -2020
NOx				
Turner (1995)	US electric utility industry	DEA	-1098 $/tons	-1098
Keilbach (1995)	Germany, 1990 Manufacturing industry	System of Cobb Douglas production function	-46 DM/kg	-45.6
Lee *et al.* (2002)	Korea electric power industry, 1990-1995	DEA, Non parametric directional distance function (account for inefficiency)	-17393 $/tons	-17393
Qi *et al.* (2004)	44 countries 1980-2000	Distance function combining parametric and non parametric approach	-40274 in 1995 $/tons	-49502.3
Salnykov and Zelenyuk (2005)	96 countries, 1995	Output distance function, parametric and non parametric	Between -6763.7 to -264150 $/tons depending on the method	Between -6763.7 to -264150
Resek and Campbell (2007)	United States, 260 coal power plants, 1998	Output distance function	Wrongly signed	Wrongly signed
Mekaroonreung and Johnson (2012)	United States coal power plants,, 2000-2008	Stochastic semi-non parametric envelopment of data Composite Deterministic	Between -409 and -1352 $/ton And between -3671 and -11679 $/ton	Between -409 and -11679
PM$_{10}$				
Keilbach (1995)	Germany, 1990 Manufacturing industry	System of Cobb Douglas production function	-87 DM/kg	-0.086
Aiken *et al.* (2003)	two-digit sic manufacturing industries, 1970-1996	output distance function	-0.7 $/tons in petroleum refining to -352.1 in printing and publishing	Between –0.7 and -352.1
Qi *et al.* (2004)	44 countries, 1980-2000	Distance function combining parametric and non parametric approach	-11461 in 1995 $/ton	14087

2. METHODOLOGY TO ESTIMATE SHADOW PRICES

Theoretical framework

This paper relies on an output distance function and its duality with a revenue function. Such approach has been widely used in the economic literature (Färe *et al.*, 1989, 1993, 2005, 2010; Kumar and Rao, 2002; Hu, 2006; Murty *et al.*, 2002).

Definition of the output distance function

The output distance function measures the distance between existing technologies and the frontier of efficiency, where a technology is said efficient if no other technology producing a higher level of output for a given set of inputs exists. Following Cuesta *et al.* (2009), D the output distance function is defined as follows

(1) $$D(x,y,w) = inf\left\{\varphi > 0 : (x, \frac{y}{\varphi}, w) \in T\right\}$$

T is the production possibility set that defines how a set of inputs x can be combined to produce the output vector (y,w). y stands for the desirable output (in the empirical work presented here, GDP) and w the undesirable output (pollutants). As φ varies so will the quantity of desirable output (y) in the production process.

The output distance function ranges from 0 to 1 and satisfies the following properties:

(i) homogenous of degree 1 in desirable output;

(ii) non-decreasing in desirable outputs;

(iii) non-increasing in undesirable outputs and in inputs;

(iv) weak disposability, meaning that a firm can only reduce undesirable outputs by decreasing simultaneously desirable output.

Duality to derive shadow prices

Using the Shephard duality lemma between the output distance function and the revenue function, shadow prices can be derived from the maximization of the revenue function over quantities (Shephard, 1970).

Following Färe et *al.* (1993), undesirable output shadow prices are the solution of the following maximization problem :

(2) $$\begin{cases} \max_{y,w} \; p_y y + p_w w \\ s.c. \; D(x,y,w) \leq 1 \end{cases}$$

Where $R(x, p_y, p_w) = p_y y + p_w w$ is the revenue function, $pw = (pw_1 \dots pw_R)$ and $py = (py_1 \dots py_M)$ respectively the shadow price of undesirable output and of desirable output, with $w = (w_1 \dots w_R)$ and $y = (y_1 \dots y_M)$ the associated quantities. In such a framework, p_w is expected to be negative.

The Lagrangian maximisation problem to be resolved is

(3) $$Max\ \Lambda = p_y y + p_w w + \lambda(D(x,y,w) - 1)$$

Calling λ the Lagrangian multiplier, the first order conditions are

$$\begin{cases} (4)\ \forall m\ \dfrac{\partial\lambda}{\partial y_m} = p_{ym} + \lambda\dfrac{\partial D(x,y,w)}{\partial y_m} = 0 \\ (5)\ \forall r\ \dfrac{\partial\lambda}{\partial w_r} = p_{wr} + \lambda\dfrac{\partial D(x,y,w)}{\partial w_r} = 0 \end{cases}$$

In the case where there is only one desirable output, $y = y_m$

(4) gives $\lambda = -\frac{p_y}{\frac{\partial D(x,y,w)}{\partial y}}$ and thus

(5) becomes $p_{wr} = \frac{p_y}{\frac{\partial D(x,y,w)}{\partial y}} \frac{\partial D(x,y,w)}{\partial w_r}$

Using the mathematical property $\frac{\partial lnD}{\partial lny} = \frac{y}{D}\frac{\partial D}{\partial y}$, the shadow price for a given undesirable output p_{wr} can be re-written as follows

(6) $$p_{wr} = p_y\ \frac{y}{w_r}\frac{\frac{\partial lnD(x,y,w)}{\partial lnw_r}}{\frac{\partial lnD(x,y,w)}{\partial lny}}$$

The homogeneity properties of degree one on desirable output of the output distance function, gives

(7) $$lnD(x,y,w) = ln[yD(x,1,w)] = lny + lnD(x,1,w)$$

Thus, the derivative of the output distance function with respect to lny is $\frac{\partial lnD(x,y,w)}{\partial lny} = 1$.

Let us call $e(y, w_r) = \frac{\partial lnD(x,y,w)}{\partial lnw_r}$ the elasticity of the output distance function with respect to the undesirable output at the frontier. As D is non increasing in undesirable output, e is expected to be negative.

Equation (7) gives $\frac{\partial lnD(x,y,w)}{\partial lnw_r} = \frac{\partial lnD(x,1,w)}{\partial lnw_r}$, which means that the elasticity *vis-à-vis* bad output of the output distance function coincides with those of the production function at the frontier of efficiency.

Finally, the shadow price can be expressed as

(8) $$\boxed{p_{wr} = p_y\ \frac{y}{w_r}\ e(y, w_r)}$$

Parametric functional form

A translog functional form is used to parametrise the output distance function and compute the derivative of the output distant function with respect to lnw_r. Such a function satisfies the conditions set above in terms of separability in input or output, as well as constant return to scale, implying it is homogenous of degree 1 in input. It provides a flexible approximation to the unknown production technology.

(9) For i = 1,..., N,

$$lnD(x,y,w) = \alpha_0 + \sum_{k=1}^{K} \alpha_k lnx_{ki} + \frac{1}{2}\sum_{k=1}^{K}\sum_{l=1}^{K} \alpha_{kl}\, lnx_{ki} lnx_{li} + \sum_{m=1}^{M} \beta_m lny_{mi}$$
$$+\frac{1}{2}\sum_{m=1}^{M}\sum_{n=1}^{M} \beta_{mn}\, lny_{mi} lny_{ni} + \sum_{r=1}^{R} \gamma_r lnw_{ri} + \frac{1}{2}\sum_{q=1}^{R}\sum_{s=1}^{R} \gamma_{qs}\, lnw_{qi} lnw_{si}$$
$$+\sum_{k=1}^{K}\sum_{m=1}^{M} \delta_{km}\, lnx_{ki} lny_{mi} + \sum_{k=1}^{K}\sum_{r=1}^{R} \varepsilon_{kr}\, lnx_{ki} lnw_{ri} + \sum_{m=1}^{M}\sum_{r=1}^{R} \rho_{mr}\, lny_{mi} lnw_{ri}$$

Equation (9) cannot be estimated as such as D is not observable.

Using the homogeneity property of D in y gives

(10) $-lny = lnD(x,1,w) - lnD(x,y,w)$

As $ln(y/y) = 0$, all terms involving lny in $lnD(x,1,w)$ are equal to zero and thus

(11)

$$\mathrm{lnD}(x,1,w) = \alpha_0 + \sum_{k=1}^{K} \alpha_k lnx_{ki} + \frac{1}{2}\sum_{k=1}^{K}\sum_{l=1}^{K} \alpha_{kl}\, lnx_{ki} lnx_{li} + \sum_{r=1}^{R} \gamma_r lnw_{ri} + \frac{1}{2}\sum_{q=1}^{R}\sum_{s=1}^{R} \gamma_{qs} lnw_{qi} lnw_{si}$$
$$+\sum_{k=1}^{K}\sum_{r=1}^{R} \varepsilon_{kr}\, lnx_{ki} lnw_{ri}$$

And (12) $e(y,w_r) = \gamma_r + \frac{1}{2}\sum_{s=1}^{R}(\gamma_{rs} + \gamma_{sr}) lnw_{si} + \sum_{k=1}^{K} \varepsilon_{kr} lnx_{ki}$

Following Aigner *et al.* (1977), equation (11) is estimated using the stochastic frontier analysis (SFA).

(13)

$$-\ln(y) = \alpha_0 + \sum_{k=1}^{K} \alpha_k lnx_{ki} + \frac{1}{2}\sum_{k=1}^{K}\sum_{l=1}^{K} \alpha_{kl}\, lnx_{ki} lnx_{li} + \sum_{r=1}^{R} \gamma_r lnw_{ri} + \frac{1}{2}\sum_{r=1}^{R}\sum_{s=1}^{R} \gamma_{rs} lnw_{ri} lnw_{si} + \sum_{k=1}^{K}\sum_{r=1}^{R} \varepsilon_{kr}\, lnx_{ki} lnw_{ri} + u_i + \omega_i$$

The residual of this equation can be broken into two distinct parts:

- the inefficiency *i.e.* the distance that separates a firm from the production frontier : $lnD(x,y,w) = -u_i$. The latter can be invariant over time or time-varying (Beloti *et al.*, 2012). Given the scope of the analysis that covers a long period spanning between 1990 and 2008, u_i is assumed to vary over time and follow a half normal distribution (Battese and Coelli, 1995).

- a statistical noise :ω_i is the standard error term and follow a normal distribution.

In the paper, equation (8) is used to compute shadow prices for pollutants, with the different parameters being derived from the estimation of (13).

Interpretation of shadow prices

Shadow prices measure the opportunity cost on the desirable output of reducing the undesirable outputs at the actual mix of output (Färe *et al.*, 1993). The latter may or may not be consistent with the maximum allowable under regulation. The higher the value of the shadow price, the higher the opportunity cost of achieving an additional reduction in the production of undesirable outputs.

High shadow prices point to the weakness of a country's regulations and/or the lack of compliance with regulations. Indeed, the regulatory framework may entice plants to adopt more efficient technologies so as to reduce their emission of pollutants while holding constant their level of desirable output. However, environment regulations are not the only factor at play. Technological improvement may indirectly occur driven by other factors such as the implementation of structural policies or change in the international business environment, leading to cleaner production processes.

It should be noted, however, that in this framework technology is measured at the aggregate national level, masking sectoral differences in the production process. Specifically, less industrialised economies are likely to produce smaller quantities of pollutant per unit of GDP compared to more industrialised ones. As such, results should not be solely interpreted in terms of country efficiency.

3. EMPIRICAL APPROACH

Data

In this paper, the focus is on key air pollutants: carbon dioxide (CO_2), the generic term NOx (which includes nitric oxide and nitrogen dioxide), sulphur oxide (SOx) and particulate matter (PM). Fossil fuel combustion is responsible for the emissions of those gases, but other sources include wildfire, agricultural burning or waste incineration.

CO_2 emissions from fuel combustion, NOx and SO_2 emissions are coming from the OECD Air and Climate database and are expressed in tons CO_2 equivalent. CO_2 emissions are from energy use and industrial process only, and exclude effects of land-use and forestry. Such measure is consistent with a production function approach. PM_{10} are expressed in tons and are extracted from the Emission Database for Global Atmospheric Research (EDGAR). They are estimated using a model from the National Institute for Public Health and the Environment, the Netherlands (RIVM). All data have been downloaded from the EDGAR (v.4.2) and are available for 19 OECD countries for the period 1970-2008. Summary statistics are reported in Annex 1.

According to these data, there has been a global trend toward reduced emissions of most gases in OECD countries between 1990-2008 (Figure 1, Figure 2).

- The United States, and to a lesser extent Japan and Germany have been the strongest emitters of CO_2 emissions on average over the period 1990-2008. Developments have differed markedly from one country to another. While emissions have risen in the United States, they have dropped in Korea and Germany (see Figure 2).

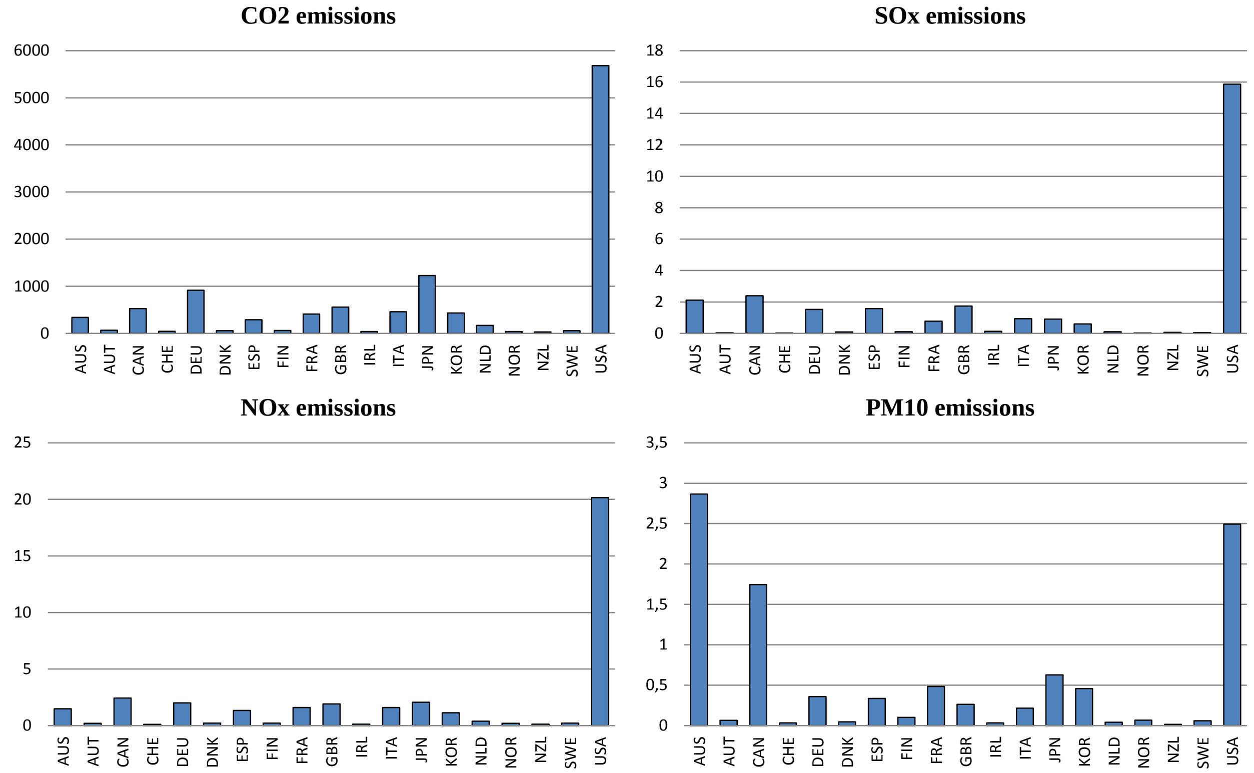
- SOx emissions were the highest in the United States. Compared to 1990 levels, those emissions have declined in almost all OECD countries. The reduction has been particularly important in European countries where environmental policies were implemented earlier.

- Decreases in NOx emissions have been less important and have occurred more recently. Reductions have been significant in Europe thanks to the Sofia Protocol designed to stabilise NOx emissions by the end of 1994 to their 1987 levels, although not all European countries achieved this objective (Scapecchi, 2008).

- PM_{10} emissions appeared to be elevated in Australia, the United States and Canada. They have markedly decreased, particularly in Europe reflecting improved vehicle engine technology and better controlled stationary fuel combustion.

Figure 1. Gas emissions

Average 1990-2008, thousand tons[1]



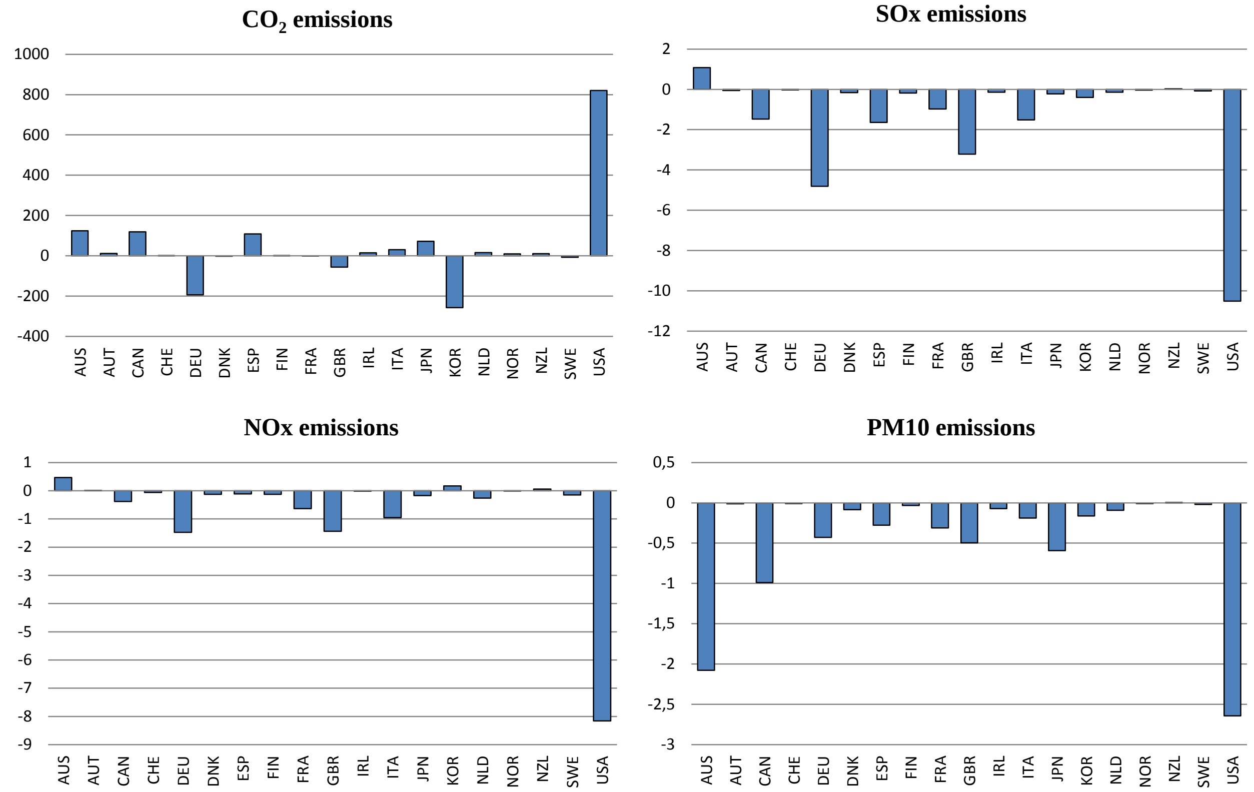
1. The unit is tons equivalent CO_2 for SOx, NOx and tons for PM_{10}.

Source: OECD Air and Climate and EDGAR.

Regarding the other components of the production function, good output data (GDP) is expressed in 2005 USD PPP and is taken from the OECD productivity database (http://www.oecd.org/std/productivity-stats/). Capital stocks are taken from the same source. Labour is measured by total employment and comes from the OECD Economic Outlook database. Tests using employment series from the Productivity database resulted into very volatile labour elasticities estimates. Finally, an indicator of natural resources has been aggregated using extraction data are from the World Bank's wealth dataset. It covers the period 1990 to 2008 and gathers information on a number of sub-soil assets, including oil, gas, bauxite, copper, lead, nickel, phosphate, tin, zinc, gold, silver, iron ore, soft and hard coal and timber. More information on how these data have been constructed can be found in World Bank (2011). The absence of a complete set of volume and price data on water, land and renewable resources such as fish stocks, precludes their inclusion in the analysis despite their importance for some OECD economies.

Figure 2. Difference over time of gas emissions

Differences 2008-1990, tons[1]


CO_2 emissions

SOx emissions

NOx emissions

PM10 emissions

1. The unit is tons equivalent CO_2 for SOx, NOx and tons for PM_{10}.

Source: OECD Air Climate Database and EDGAR.

Estimation procedure

Equation (13) is estimated using Stochastic Frontier Analysis SFA (Murty and Kumar, 2002; Färe *et al.*, 2004; Cuesta *et al.*, 2009). Air pollutants, CO_2, SOx, NOx and PM_{10}, have been incorporated separately in the translog function to control for the potential cross correlation between pollutants, given that they are all mostly produced during the combustion process. Although from a scientific viewpoint, the relationships between the different pollutants are not known with certainty, there is empirically evidence that the various pollutants are relatively well correlated (Table 2). Output elasticities are derived from a linear combination of the frontier parameters and their significance is statistically tested. Estimates account for heterogeneity across countries and over time.

One of the main difficulties of the approach is to estimate e (w,yr), the elasticity of gas emissions to output. Indeed, this requires not only to estimate the parameters from equation (13) but also to quantify the logs of inputs and undesirable outputs variables, which are coming from the derivatives of the translog's cross-terms. Observed input and undesirable output data that vary across time and countries cannot be used as proxies, as these terms should be derived from the most efficient production and for country specific production scale. In addition, the computation also has to cope with measurement errors, which can be significant for some gas emission data or the stock of natural resource. *In fine*, using observed data could lead to implausible volatility of elasticities and in turn of shadow prices.

Table 2. Correlations across pollutants

	CO_2	NOx	SOx	PM_{10}
CO_2	1.00			
NOx	0.97*	1.00		
SOx	0.94*	0.99*	1.00	
PM_{10}	0.53*	0.58*	0.63*	1.00

Note: A star means the correlation is significant at 1%.

Source: Authors' calculations.

Against this background, elasticities have been computed at the mean value of the sample (see Aiken and Pasurka (2003) for a similar approach). While in principle, these elasticities can vary along the frontier of efficiency and decline in line with higher production scales, computing an average across countries is a way to proxy the elasticity that would apply to a representative country.

4. SHADOW PRICE ESTIMATES

The estimation of factor elasticity gives sensible results. In particular, elasticities for capital and natural resources are stable across all the models and of reasonable order of magnitude, around 0.3-0.4 for capital and 0.02-0.1 for natural resource (Table 3). Labour output elasticity varies somewhat across estimates. It remains nonetheless of plausible magnitude in all cases.

The production of output is statistically and significantly associated with those of CO_2 emissions. Estimates of CO_2 elasticity are found to be around 0.15 and are significant. NOx and PM_{10} elasticities would be of lower amplitude. By contrast, SOx elasticity is estimated to be not significantly different from zero. It was thus not possible to derive shadow prices for this pollutant. Full estimation results can be found in Annex 2.

Elasticities reported in Table 3 are used to derive shadow prices for CO_2, using formula 8. Shadow prices for CO_2, SOx, NOx are expressed in 2005 PPP USD per ton of equivalent CO_2. Shadow prices for PM_{10} are in 2005 PPP USD per ton of PM_{10}. For sake of simplicity, the unit is 'USD per ton' in what follows.

As the elasticity of pollutant to output is set at the sample average, the intensity ratio (output per emissions in thousands USD) and the value of the output price explains all the differences across country or over time. In addition, the intensity ratio which is about 100 to 1000 times higher for SOx, NOx and PM_{10} than for CO_2, explains a large part of the difference in the order of magnitude of the shadow prices for CO_2 and those of the other gases.

CO_2 shadow prices in most countries are estimated to be around -400 and -500 USD per ton (Table 4). These estimates appear to be within the range of existing estimates in the literature, which range from almost - 500 USD per ton of CO_2 to a very high level of -0.01 in some countries (Table 1).

Table 3. Elasticity estimates to output

Elasticity	*Capital*	*Labour*	*Natural resource*	*CO_2*	*SO_X*	*NO_X*	*PM_{10}*
CO_2	0.30	0.58	0.02	0.15			
p-value	*0.00*	*0.00*	*0.00*	*0.00*			
SO_X	0.41	0.73	0.06		-0.01		
p-value	*0.00*	*0.00*	*0.05*		*-0.79*		
NO_X	0.33	0.74	0.02			0.07	
p-value	*0.00*	*0.00*	*0.01*			*0.00*	
PM_{10}	0.29	0.75	0.04				0.02
p-value	*0.00*	*0.00*	*0.00*				*0.00*

Note: Output elasticities of pollutants are computed using coefficients of the translog function and mean values. The figures are shown with positive values for convenience, but estimates from equation (13) are all negatively signed. A p-value exceeding 0.05 indicates that the elasticity is not significant at 5%.

Source: Authors' calculations.

The lowest CO_2 shadow prices (in absolute values) are found for Australia and Canada reaching an average value of around USD -240 and the highest in Switzerland, Sweden, France and Norway (almost -800 USD per ton). This finding is consistent with the observed level of fuel taxation in individual countries. While fuel is lightly taxed in Australia and Canada, it is relatively heavily taxed in Sweden and Norway.

Developments in CO_2 shadow prices over the 1990 2008 period suggest that all countries but Korea have strengthened their regulatory framework and encouraged the adoption of clean technologies (Figure 3). Sweden, Norway and Ireland experienced the sharpest decrease in CO_2 shadow prices, pointing to deeper efforts to adopt cleaner technologies than in peer countries. Most countries stepped up efforts in the 2000s leading to a faster decrease in shadow prices during this decade compared to the preceding one (Annex 3). Korea stands out as an exception: after a rise in shadow prices in the 1990s, the latter start declining marginally in the 2000s.

NOx shadow prices are estimated to be much lower than CO_2 prices, reflecting a higher output-to-emissions ratio. Prices generally range between -40000 and -80000 USD per ton on average over the period 1990-2008. Switzerland and to a lesser extent Japan, the Netherlands and Sweden display lower shadow prices than average. All the countries experienced a marked fall over time, with the most significant declines being observed in the Netherlands, the United Kingdom and Ireland (Figure 4).

These shadow prices seem to be quite elevated in absolute terms, but they appear to be within the range of existing estimates from the literature which arguably is very large (from -46 to -49000 USD per ton). Qi *et al.* (2004) also estimate NOx shadow prices for 26 OECD countries that are 160 higher than CO_2 prices. It should be noted, however, that other papers came up with lower estimates of less than -25 000 USD per ton (see for instance Lee *et al.*, 2002; or more recently Mekaroonreung and Johnson, 2012). Both differences in geographical scope and in methodologies explain the wide range of shadow price estimates.

Table 4. Shadow prices and ratio of output over emissions

Average 1990-2008

	Shadow prices			Output/emissions,		
	2005 USD PPP per ton of CO_2		2005 USD PPP per ton of PM_{10}	Thousand USD per ton		
	CO_2	NO_X	PM_{10}	CO_2	NO_X	PM10
Australia	-238	-26,259	-5,079	1.7	394	257
Austria	-501	-81,296	-72,880	3.5	1,185	3,735
Canada	-245	-26,372	-17,216	1.8	391	866
Switzerland	-786	-161,298	-152,181	5.7	2,356	8,005
Germany	-365	-85,482	-138,878	2.7	1,267	7,306
Denmark	-389	-52,206	-82,161	2.7	744	4,173
Spain	-455	-49,397	-65,101	3.4	742	3,343
Finland	-321	-44,547	-26,902	2.2	627	1,356
France	-564	-73,093	-72,535	4.1	1,070	3,726
United Kingdom	-416	-64,398	-206,938	3.0	941	10,400
Ireland	-386	-64,538	-81,112	2.8	938	4,129
Italy	-475	-72,818	-152,850	3.3	1,026	7,654
Japan	-410	-118,409	-131,427	3.0	1,770	6,712
Korea	-260	-50,403	-57,442	1.9	732	2,844
Netherlands	-397	-91,594	-295,832	2.9	1,354	15,400
Norway	-570	-56,467	-50,083	4.6	923	2,831
New-Zealand	-396	-44,837	-101,999	2.7	645	5,173
Sweden	-672	-86,862	-87,699	4.5	1,191	4,319
United States	-255	-37,270	-92,191	1.8	545	4,716

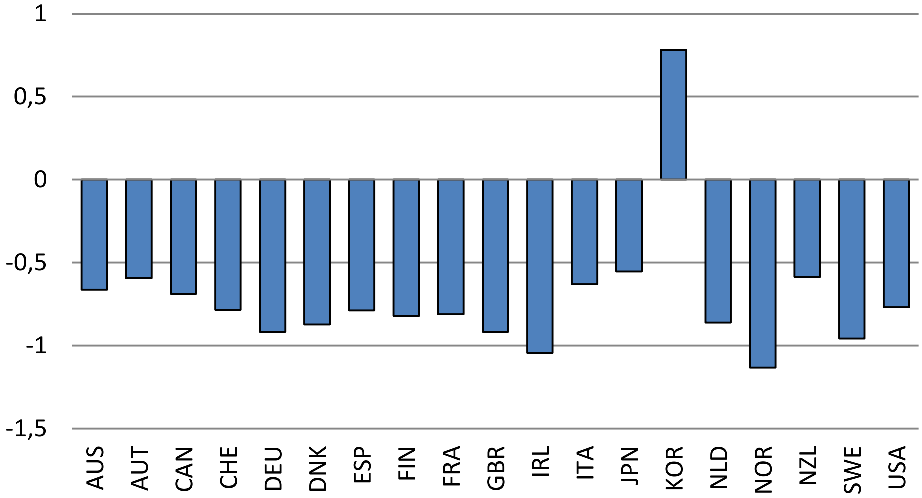
Source: Authors' calculations.

Amongst the various air pollutants, PM_{10} is probably the one for which there is less evidence in the literature. Prices presented in this paper appear to be on the low side compared to existing estimates, reflecting both differences in methods and scope across the various studies. In most countries, those prices are in between -50 000 and -15 000 USD per ton. Shadow prices are particularly low in the Netherlands and the United Kingdom. They declined the most over the period 1990-2008 in Australia and Korea (Figure 5). Contrary to what observed for CO_2 and NOx, steep declines have occurred in both the 1990-2000 and the 2000-2008 sub-periods.

Estimated shadow prices of PM_{10} are those that display the highest variability across countries. Qi *et al.* (2004) also found a very large variability of shadow price estimates across OECD countries. In the same vein, looking at the two-digit sic manufacturing industries over the period 1970-1996 in the United States, Aiken *et al*. (2003) observed a large variability across industries, with price in the printing and publishing sector being some 300 times lower than those in petroleum refining.

Figure 3. CO_2 shadow prices

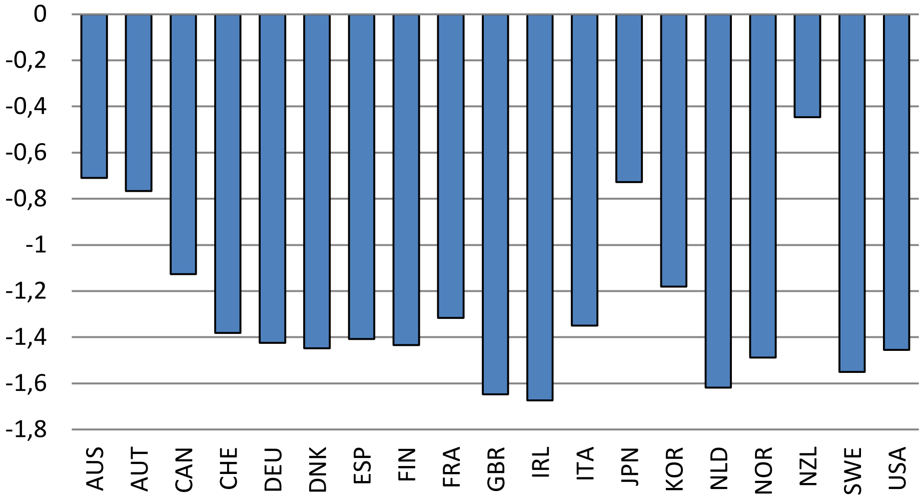
Difference 2008-1990, Index 1 in 2000



Source: Authors' calculations.

Figure 4. NOx shadow prices

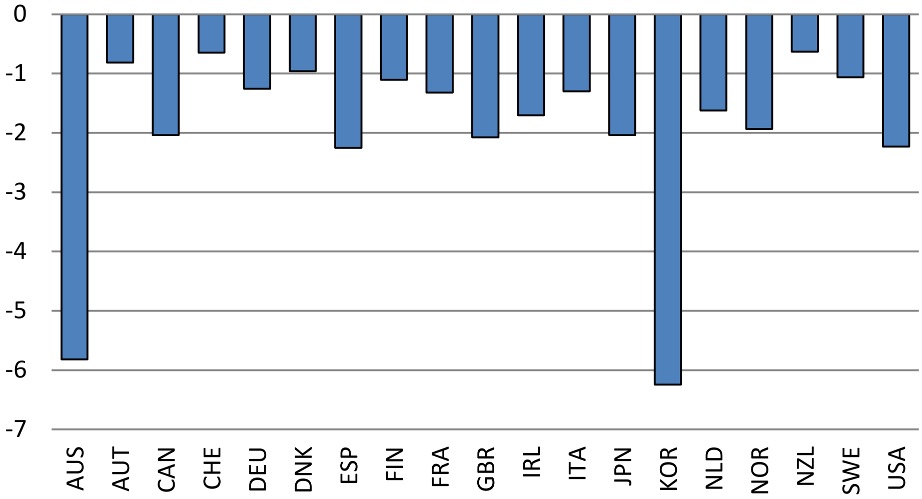
Difference 2008-1990, Index 1 in 2000



Source: Authors' calculations.

Figure 5. PM10 shadow prices

Difference 2008-1990, Index 1 in 2000



Source: Authors' calculations.

CONCLUSION

The objective of this paper is to estimate time-varying country-specific shadow price of pollution. The approach relies on an output distance function, which has been estimated for 19 OECD countries over the period 1990-2008. Similar empirical analysis could easily be replicated to other countries or other pollutants than those already tested in this work.

Significant and correctly-signed shadow prices have been estimated for CO_2, NOx and PM_{10}. Shadow prices for pollutants are found to vary widely across countries, depending on national environmental regulations, the use of inefficient abatement technologies and the structure of the economy. Shadow prices for PM10 are those that display the highest variability across countries. For most air pollutants, estimates suggest that OECD countries have strengthened their regulatory framework and encouraged the adoption of clean technologies, especially since the 2000s.

The analysis is subject to a number of caveats. First, given the difficulty to find reliable data in this area, it was only possible to include a limited number of pollutants in the analysis.

Second, the analysis has been undertaken at a very aggregate level and can hide wide disparities across sectors or firms. In this regard, undertaking a similar exercise at the sectoral or firm level is likely to be very informative.

Finally the estimation method could be refined to better account for country heterogeneity. One extension of the work could be for instance to better capture the output-undesirable output elasticity, and try other proxies than the average sample used in this paper. Ideally, it would be better to estimate country-specific elasticity but this may require changing the framework to be able to test the significance of these elasticities. More importantly, such analysis requires to be complemented by measures of uncertainties surrounding shadow prices estimates to guide their use at the policy level.

BIBLIOGRAPHY

Aigner, D.J., C. Lovell and P. Schmidt (1977), "Formulation and Estimation of Stochastic Frontier Models", *Journal of Economy,* 6, 21-37.

Aigner, D.J. and S.F. Chu (1968), 'On Estimating the Industry Production Function', *American Economic Review*, Vol. 13, 826– 839.

Aiken D.V. and C. Pasurka Jr (2003), "Adjusting the Measurement of US Manufacturing Productivity for Air Pollution Emissions Control", *Resource and Energy Economics* 25, 329-351.

Australian Productivity Commission (2011), *Carbon Emission Policies in Key Economies, Productivity Commission Research Report*, Camberra.

Bellotti F., S. Daidone, G. Ilardi and V. Atella (2012), "Stochastic Frontier Analysis Using Stata", *Center for Economic and International Studies Research Paper Series*, Vol. 10, Issue 12, No 251, September.

Boyd, G., J. Molburg and R. Prince (1996), "Alternative Methods of Marginal Abatement Cost Estimation: Non-parametric Distance Function", *Proceedings of the USAEE/IAEE 17th Conference*, 86–95.

Brunel C. and A. Levinson (2013), "Evaluating Measures of Environmental Regulatory Stringency", Georgetown University.

Coggins, J. S. and J. R. Swinton (1996), "The Price of Pollution: A Dual Approach to Valuing SO_2 Allowances", *Journal of Environmental Economics and Management*, Vol. 30, 58-72.

Cuesta R. A, C.A. Knox Lovell, J.L. Zofio (2009), "Environmental Efficiency Measurement with Translog Distance Functions: A Parametric Approach", *Ecological Economics*, Vol. 68, 2232-2242.

Färe R, S. Grosskopf, D. Margaritis (2010), "Directional Distance Functions and Applied Economics, A Tribute to R.G. Chambers", mimeo.

Färe R, S. Grosskopf, D. Noh and W. Weber (2005), "Characteristics of a Polluting Technology: Theory and Practice", *Journal of Econometrics*, Vol. 126, 469-492.

Färe R, S. Grosskopf, C.A. Knox Lovell and S. Yaisawarng (1993), "Derivation of Shadow Prices for Undesirable Outputs: A Distance Function Approach", *The Review of Economics and Statistics*, Vol 75(2), 374-380.

Färe R., S. Grosskopf, C. A. K. Lovell and C. Pasurka (1989), "Multilateral Productivity Comparisons when some Ouputs are Undesirable: A non Parametric Approach", *The Review of Economics and Statistics*, Vol. 71, No. 1, 90-98.

Hu J.L. (2006), “Efficient Air Pollution Abatements of Regions in China”, *International Journal of Sustainable Development and World Ecology*, 13:4, 327-340.

Keilbach, M. (1995), “Estimation of the Value of the Marginal Product of Emissions in a Country where Emissions Output is Regulated – An Empirical Study”, *Environmental and Resource Economics*, Vol. 5, 305-319.

Kumar S. and D. N. Rao (2002), “Estimating Marginal Abatement Cost of SPM: An Application to the Thermal power Sector in India”, *Energy Studies Review*, 11, 76-92.

Kuosmanen (2006), “Stochastic Nonparametric Envelopment of Data: Combining Virtues of SFA and DEA in a Unified Framework”, *MIT Discussion Paper*, 3, 1-51.

Lee, J.D., J.B. Par T.Y. Kim (2002), “Estimation of the Shadow Prices of Pollutants with Production/Environment Inefficiency Taken into Account: a Nonparametric Directional Distance Function Approach”, *Journal of Environmental Management*, Vol. 64, Issue 4, 365–375.

Maradan D. and A. Vassiliev (2005), “Marginal Costs of Carbon Dioxide Abatement: Empirical Evidence from Cross-Country Analysis”, *Schweizerische Zeitschrift für Volkswirtschaft une Statistik*, Vol. 34, 723-32.

Mekaroonreung, M. and A. L. Johnson (2012), “Estimating the Shadow Prices of SO_2 and NO_X for U.S. Coal Power Plants: A Convex Nonparametric Least Squares Approach”, *Energy Economics*, Vol. 34, 723-732.

Merk O. and T. T. Dang (2012), “Efficiency of World Ports in Container and Bulk Cargo (oil, coal, ores and grain)”, *OECD Regional Development Working Papers 2012/9*, OECD Publishing.

Murty, M.N and S. Kumar (2002), “Measuring Cost of Environmentally Sustainable Industrial Development in India: A Distant Function Approach”, *Environment and Developments Economics*, Vol. 7, Issue 3.

Qi S., L. Xu and J. Coggins (2004), “Deriving Shadow Prices of Environmental Externalities”, University of Minesota.

Rezek, J. P. and R. C. Campbell (2007), “Cost Estimates for Multiple Pollutants: A Maximum Entropy Approach”, *Energy Economics*, Vol. 29, 503-519.

Salnykov M. and V. Zelenyuk (2005), "Estimation of Environmental Efficiencies of Economies and Shadow Prices of Pollutants in Countries in Transition," *EERC Working Paper Series* 05-06e, EERC Research Network, Russia and CIS.

Scapecchi P. (2008), “The Health Costs of Inaction with Respect to Air Pollution”, *OECD Environment Working Paper*, No.2.

Schreyer P. (2010), “Measuring Multi-factor Productivity when Rates of Return Are Exogenous”, Chapter 2, pp. 13-40 in W.E. Diewert, B.M. Balk, D. Fixler, K.J. Fox and A.O. Nakamura (2010), *Price and Productivity Measurement*, Volume 6, Trafford Press.

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

Swinton J.R. (1998), “At What Cost Do We Reduce Pollution? Shadow Prices of SO_2 emissions”, *Energy Journal*, 4, 63-83.

Turner J. (1995), “Measuring the Cost of Pollution Abatement in the US Electric Utility Industry: A Production Frontier Approach”, Doctoral dissertation, University of North Carolina, Chapel Hill.

World Bank (2011), “The Changing Wealth of Nations: Measuring Sustainable Development in the New Millennium”, *The World Bank,* Washington, USA.

Zhang, T. and E. Garvey (2008); “A Comparative Analysis of Multi-Output Frontier Models”, *Journal of Zhejiang University SCIENCE A*, 2008, 9(10):1426-1436

ANNEX 1. DATA

Standard statistics on the average over 19 countries and over the period 1990-2008 are reported in the table below.

	Observations	Mean	Standard deviation	Minimum	Maximum
CO_2	342	6.00e+08	1.24e+09	2.50e+07	6.11e+09
SO_2	342	1,56E+06	3,62E+06	14165.16	2.09e+07
NOx	342	2,00E+06	4,46E+06	88775.83	2.30e+07
PM_{10}	342	559034.5	933336.8	13448.1	4524650
GDP	342	1.39e+12	2.35e+12	6.37e+10	1.31e+13
Capital	342	1.58e+14	4.70e+14	1.00e+11	1.96e+15
Labour	342	2.07e+07	3.04e+07	1155575	1.46e+08
Natural resource	342	2.51e+10	5.15e+10	1.02e+08	2.44e+11

ANNEX 2: SFA ESTIMATION RESULTS

Variable	**CO_2**	**NOx**	**SOx**	**PM10**
lnCAPV	-0.2943***	-0.3225***	-0.3616***	-0.2406***
lnLABV	-0.5967***	-0.7276***	-0.7282***	-0.8051***
lnNATV	-0.0172*	-0.0201*	-0.0608	-0.0446***
lnCO2	-0.1414***			
lnCAPVSQ	0.3531	0.3031	1.8281**	1.9479***
lnLABVSQ	6.0920***	0.9092	8.0399	9.1921***
lnNATVSQ	-0.0127	0.0760	0.0051	-0.1105
lnCO2SQ	1.4428*			
lnCAPV_lnLABV	-2.1678**	0.8062	-2.7000**	-4.0298***
lnCAPV_lnNATV	0.5038***	0.4265*	0.3220	0.5988**
lnLABV_lnNATV	-0.7251**	-0.6804*	-0.0327	-0.5274
lnCAPV_lnCO2	-0.0701***			
lnLABV_lnCO2	0.3300*			
lnNATV_lnCO2	-0.3113*			
lnNOX	-0.0701***			
lnNOXSQ	0.3300*			
lnCAPV_lnNOX	-0.3113*			
lnLABV_lnNOX	0.9251**			
lnNATV_lnNOX	0.0964			
lnSOx	0.0197			
lnSOxSQ	0.1350*			
lnCAPV_lnSOx	0.3187			
lnLABV_lnSOx	0.0669			
lnNATV_lnSOx	-0.0319			
lnPM10	-0.0193**			
lnPM10SQ	0.0011			
lnCAPV_lnPM10	0.4385***			
lnLABV_lnPM10	-0.5525***			
lnNATV_lnPM10	-0.0891*			
constant	0.1101***	0.0975***	0.0335	0.1140***
Statistics				
Observations	342	342	342	342
Log-likelihood	728.2065	726.5209	698.9533	709.4258
chi2	3.89e+04	4.37e+04	9308.4712	1.11e+04
AIC	-1.35e+03	-1.35e+03	-1.30e+03	-1.32e+03

legend: * p<0.05; ** p<0.01; *** p<0.001

Times and country dummy have been introduced in the estimation

ANNEX 3. AVERAGE DECREASE IN SHADOW PRICES

		CO_2	NOx	PM_{10}
Australia	1990-2008	-0,03	-0,04	-0,31
	1990-2000	-0,03	-0,03	-0,03
	2000-2008*	-0,04	-0,04	-0,61
Austria	1990-2008	-0,03	-0,04	-0,04
	1990-2000	-0,03	-0,03	-0,04
	2000-2008*	-0,03	-0,05	-0,04
Canada	1990-2008	-0,04	-0,06	-0,11
	1990-2000	-0,02	-0,03	-0,06
	2000-2008*	-0,05	-0,08	-0,15
Switzerland	1990-2008	-0,04	-0,07	-0,03
	1990-2000	-0,03	-0,04	-0,05
	2000-2008*	-0,06	-0,10	-0,01
Germany	1990-2008	-0,05	-0,07	-0,07
	1990-2000	-0,04	-0,05	-0,06
	2000-2008*	-0,06	-0,10	-0,06
Denmark	1990-2008	-0,05	-0,08	-0,05
	1990-2000	-0,03	-0,05	-0,08
	2000-2008*	-0,06	-0,10	-0,01
Spain	1990-2008	-0,04	-0,07	-0,12
	1990-2000	-0,02	-0,03	-0,06
	2000-2008*	-0,07	-0,12	-0,18
Finland	1990-2008	-0,04	-0,08	-0,06
	1990-2000	-0,03	-0,05	-0,04
	2000-2008*	-0,05	-0,10	-0,07
France	1990-2008	-0,04	-0,07	-0,07
	1990-2000	-0,03	-0,04	-0,05
	2000-2008*	-0,05	-0,10	-0,08
United Kingdom	1990-2008	-0,05	-0,09	-0,11
	1990-2000	-0,04	-0,05	-0,08
	2000-2008*	-0,05	-0,12	-0,14
Ireland	1990-2008	-0,05	-0,09	-0,09
	1990-2000	-0,04	-0,05	-0,08
	2000-2008*	-0,07	-0,13	-0,09
Italy	1990-2008	-0,03	-0,07	-0,07
	1990-2000	-0,03	-0,05	-0,06
	2000-2008*	-0,04	-0,09	-0,08
Japan	1990-2008	-0,03	-0,04	-0,11
	1990-2000	-0,02	-0,02	-0,05
	2000-2008*	-0,04	-0,05	-0,17
Korea	1990-2008	0,04	-0,06	-0,33

	1990-2000	-0,02	-0,04	0,01
	2000-2008*	0,11	-0,08	-0,70
The Netherlands	1990-2008	-0,05	-0,09	-0,09
	1990-2000	-0,04	-0,06	-0,08
	2000-2008*	-0,05	-0,11	-0,09
Norway	1990-2008	-0,06	-0,08	-0,10
	1990-2000	-0,04	-0,04	-0,04
	2000-2008*	-0,08	-0,11	-0,17
New-Zealand	1990-2008	-0,03	-0,02	-0,03
	1990-2000	-0,02	-0,02	-0,03
	2000-2008*	-0,04	-0,03	-0,03
Sweden	1990-2008	-0,05	-0,08	-0,06
	1990-2000	-0,03	-0,05	-0,04
	2000-2008*	-0,07	-0,11	-0,07
United States	1990-2008	-0,04	-0,08	-0,12
	1990-2000	-0,03	-0,04	-0,06
	2000-2008*	-0,05	-0,11	-0,18

www.oecd.org/greengrowth