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Capturing the least costly way of reducing pollution: A shadow price approach

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ABSTRACT

The production analysis literature is increasingly concerned with estimating marginal abatement costs. Yet, most studies do not emphasize the ways in which pollutants may be reduced and their costs, which makes them unable to identify the least costly compliance strategy. This paper utilizes the materials balance principle to relate pollution to the employment of material inputs. A production model which allows input and output substitution, downscaling of operations, pollution control, and emission permits purchases as compliance strategies is proposed, and the implications of joint and non-joint pollution controls for the trade-off between pollutants and desirable outputs are considered. Marginal abatement costs, reflecting the least costly way of compliance, are derived by exploiting the duality between the directional distance function and the profit function.

1. Introduction

The production analysis literature is increasingly concerned with environmental issues, in particular with estimating marginal abatement costs. These estimates can play an important role in identifying the costs of environmental regulations which, together with the gains from avoided environmental damage,[1] allow determining the net benefits of environmental legislation. The estimates' applicability for policy making hinges on their quality and validity. In turn, that also influences whether socially optimal outcomes or welfare increases are achieved. Models that are unable to capture the actual dynamics of pollution generation, as well as producers' options for complying with environmental regulations, are unlikely to reveal the firms' actual abatement costs.

The majority of empirical production studies that estimate marginal abatement costs apply the model framework of Färe et al. (1993, 2005) which measures marginal abatement costs by the value of forgone desirable outputs required to reduce pollutants. Yet, there is no clear explanation of how emissions are generated and how they can be reduced. The model framework is therefore not suitable for evaluating the relative costs of different compliance strategies. This is a drawback of the approach, since both common knowledge and economic theory suggest that the producers will evaluate all feasible compliance strategies before selecting the least costly option.

In the current paper, I explicitly represent the dynamics of pollution generation by the materials balance principle. It allows identifying both uncontrolled (without pollution control) and controlled (with pollution control) emissions. Whenever information on input quantities, output levels, and pollutants is provided, uncontrolled and controlled emissions, as well as pollution control efforts, can be quantified.

My approach responds to Førsund's (2009) demand for accounting for flexibility in producers' responses to environmental regulations, by offering them an opportunity to reduce their emissions by input and output substitution, downscaling of operations, or pollution control, and to purchase emission permits. Contrary to the established literature, my approach allows weighing the costs of different compliance strategies, and further to select the tool or combination of tools that minimize the producers' costs of complying with environmental regulations. Note that this perspective is in line with the interpretation of abatement costs in the environmental economics literature—the least cost approach to satisfying environmental regulations.

My approach to marginal abatement cost estimation can be considered an extension to the approach of Färe et al. (1993), where abatement costs are derived from distance function derivatives. Contrary to Färe et al. (1993), I consider polluting firms that operate under emission constraints which may be relaxed by pollution control or purchases of emission permits. Thus, the costs of pollution control and emission permits are weighed against the economic benefits of employing polluting inputs. By maximizing profits under emission

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[1] This paper follows the literature on polluting technologies by not taking consumer preferences or environmental damage into account. For a discussion on these topics, see Førsund (2009) or Färe et al. (2013).

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constraints and applying the duality of the directional distance function to the profit function, optimum conditions can be derived that allow identifying and estimating marginal abatement costs. Profit maximization is considered both when the production of desirable outputs is joint and non-joint with pollution control. I find that a positive trade-off between pollutants and desirable outputs – usually assumed by the literature on polluting technologies – is consistent with joint pollution control, while the trade-off may be both positive and negative in the case of non-joint pollution control. The solutions to the emission constrained profit problems are further shown to rationalize allocative inefficiency for firms that comply with environmental regulations. That is, requirements to reduce emissions increase the effective costs of polluting inputs relative to their market prices, since increases in their employment require additional spending to offset related increases in uncontrolled emissions. This recognition is important for properly understanding the dynamics of environmental regulation.

The paper is organized as follows. I review the production analysis literature on marginal abatement costs estimation in the following section. The method discussed makes up the foundation of the proposed procedures for abatement cost estimation in this paper. Section 3 discusses the materials balance principle, while Section 4 incorporates it in an economic model. The estimation of marginal abatement costs is further discussed, both in the case with joint and non-joint pollution controls. Section 5 discusses the extension of the abatement cost method when multiple pollutants are regulated, in addition to focusing on computational approaches. Section 6 concludes.

2. Marginal Abatement Cost Estimation in the Literature

The literature usually treats pollutants as inputs or outputs to be included in the technology. In an early attempt to estimate marginal abatement costs, Pittman (1981) incorporates pollutants as inputs in the technology. This treatment is contingent on the assumption that positive marginal productivities of pollutants, enforced by the axiom of free disposability of inputs, characterize transformation of resources from pollution control to intended productions. Pittman defines an environmentally restricted profit function and applies the Lagrangian multiplier on the regulation constraint to obtain estimates of marginal abatement costs for a sample of pulp-and-paper mills. This modeling approach has not been followed up in the literature. However, his restricted profit problem resembles the profit maximization problems found in Section 4 of this paper.

Pittman's dataset was later used by Färe et al. (1993), who introduced a new and innovative method for estimating marginal abatement costs. In their approach, pollutants (or undesirable outputs) are treated as outputs. Let $x \in \Re_+^N$ denote a vector of inputs and let $y \in \Re_+^M$ denote a vector of desirable outputs. Consider, for simplicity, only one pollutant, $b \in \Re_+$. An extended output set may then be defined:

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

Färe et al. assume that the polluting technology satisfies the standard axioms of inactivity, compact and convex output sets, and free disposability of inputs and desirable outputs. See Färe and Primont (1995) for a discussion on these properties. In addition, two non-standard axioms are imposed to accommodate for the production of bads:

(i) if $(y,b) \in P(x)$ and $b = 0$, then $y = 0$
(ii) if $(y,b) \in P(x)$ and $0 \le \theta \le 1$, then $(\theta y, \theta b) \in P(x)$.

Axiom (*i*), null-jointness (Shephard and Färe, 1974), imposes unavoidable pollution. Axiom (*ii*), weak disposability (Shephard, 1970), secures that reductions in the pollutant can be achieved by simultaneously reducing desirable outputs. According to Färe et al. (2005) this is consistent with regulations which require cleanup of pollutants, since resources are diverted from producing desirable outputs to emission reductions.

The directional output distance function is a suitable function representation for the polluting technology from Eq. (1) (Färe et al., 2005). The directional distance function was introduced in Chambers et al. (1996), Chung et al. (1997), Chambers et al. (1998), and allows defining maximum feasible translation of inputs and outputs in any pre-assigned direction. Here, it seeks simultaneous maximal reduction in the pollutant and expansions of desirable outputs. Define the direction vector $g = (g_y, -g_b)$ where $g_y \in \Re_+^M$ and $g_b \in \Re_+$, and the distance function:

$$\vec{D}_O\left(x, y, b; g_y, -g_b\right) = \sup\left\{\beta \in \Re : \left(y + \beta g_y, b - \beta g_b\right) \in P(x)\right\}. \tag{2}$$

The directional distance function inherits the properties of the parental technology. Under g-disposability,[2] the directional distance function completely characterizes the underlying polluting technology in the sense that:

$$(y, b) \in P(x) \text{ if and only if } \vec{D}_O\left(x, y, b; g_y, -g_b\right) \ge 0. \tag{3}$$

It satisfies the translation property:

$$\vec{D}_O\left(x, y + \alpha g_y, b - \alpha g_b; g_y, -g_b\right) = \vec{D}_O\left(x, y, b; g_y, -g_b\right) - \alpha, \quad \alpha \in \Re \tag{4}$$

and is homogenous of degree minus one in $(g_y, -g_b)$, non-decreasing in b, non-increasing in y, and concave in (y,b).

Eq. (3) allows defining the revenue function in terms of the distance function. Let $r \in \Re_+^M$ and $q \in \Re_+$ be vectors of (shadow) prices and define the revenue function:

$$\begin{aligned} R(x, r, q) &= \max_{y,b}\left\{ry - qb : \vec{D}_O\left(x, y, b; g_y, -g_b\right) \ge 0\right\} \\ &= \max_{y,b}\left\{ry - qb + \left(rg_y + qg_b\right)\vec{D}_O\left(x, y, b; g_y, -g_b\right)\right\} \end{aligned} \tag{5}$$

where the last equality is due to Chambers et al. (1998). The first order conditions for revenue maximization are:

$$\left(rg_y + qg_b\right)\nabla_y \vec{D}_O\left(x, y, b; g_y, -g_b\right) = -r \tag{6}$$

$$\left(rg_y + qg_b\right)\partial \vec{D}_O\left(x, y, b; g_y, -g_b\right)/\partial b = q. \tag{7}$$

For the output m and the pollutant b, it follows that their relative price equals the corresponding ratio of distance function derivatives. Hence:

$$q = -r_m \frac{\partial \vec{D}_O\left(x, y, b; g_y, -g_b\right)/\partial b}{\partial \vec{D}_O\left(x, y, b; g_y, -g_b\right)/\partial y_m}. \tag{8}$$

The shadow price q can now be obtained from Eq. (8), by assuming that the observed sales price of output y_m equals its shadow price (Färe et al., 1993). The shadow price is here interpreted as the value of desirable output that must be forgone in order to marginally reduce the pollutant. In other words, it defines the marginal abatement costs.

Färe et al.'s approach to abatement cost estimation benefits from the use of distance functions. They do not rely on price information and are therefore suitable in cases with missing prices for pollutants. Consequentially, the procedure is very popular and has been employed

[2] If $(y,b) \in P(x)$ then $(y - g_y, b + g_b) \in P(x)$.