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An Application of Leif Johansen's Capacity Model

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Abstract

The production of desirable (good) outputs is frequently accompanied by unintended production of undesirable (bad) outputs. If two or more of these undesirable outputs are produced as byproducts, one may ask: 'Which bad is worst?' By worst we mean which bad inhibits the production of desirable outputs the most if it is regulated. We develop a model based on Leif Johansen's capacity framework by estimating the capacity limiting effect of the bads. Our model resembles what is referred to as the von Liebig Law of the Minimum, familiar from the agricultural economics literature. To illustrate our model we apply our approach to a firm level data set from the Swedish paper and pulp industry.

Keywords: von Liebig Law of the Minimum, DEA, emissions, regulation.
JEL-codes: D24, Q01, Q5.

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1 Introduction

We know that industrial production of marketable outputs is frequently produced with unintended emissions that generate negative externalities. An example is the production of pulp and paper where, e.g., emissions to air, CO2, SO2, and NOx are jointly produced. From a societal point of view it is therefore of interest to pursue environmental policy and regulate firms' emissions. Given the firms' production technologies, these regulations may restrict the production of marketable good outputs and lower production and revenues. In this paper we specifically analyze to what extent firms' good output production is restricted by environmental regulation of undesirables.

The main objective is to develop a model to identify which bad output is the "worst", i.e., identifying the bad output that due to environmental regulation restricts firms' production of good outputs the most.[2] To illustrate, we apply the model to Swedish pulp and paper data at firm level covering the period 1990 to 2008, focusing especially on year 2008.

Based on Leif Johansen's capacity framework (Johansen 1968), Färe et al. (1989) developed a capacity utilization index for industrial production. Later this work formed the basis for studying von Liebig's law of the minimum in agriculture, which states that adding non-limiting nutrients to a crop field will not increase the yield from that field if there is another limiting nutrient (see, e.g., Paris, 1992). For example, Wang et al. (2006), Färe et al. (2009), and Färe et al. (2012) have identified nutrients that limit yields. This paper follows in the spirit of this literature, with the unique difference that we identify to what extent the regulation of bad outputs are limiting industrial production. To identify limiting bad outputs we apply a non-parametric Data Envelopment Analysis (DEA) model as the pollution generating technology, where bad outputs are by-products produced simultaneously with good outputs. This is made possible by imposing the technology properties of disposability and null-jointness as proposed by Färe et al. (1986). Specifically, the model gives information about firms' costs of adjusting to regulation of a specific bad output, and therefore can be used to rank the cost of regulating different bad outputs. This information may be helpful as a complement to other relevant decision variables when considering different environmental

[2] A more comprehensive approach could also consider broader societal issues such as the health and environmental impacts of the bad production, i.e., a more complete cost-benefit analysis. That is, however, beyond the scope of this paper as we only take the perspective of the firm.

policy measures. To our knowledge the particular approach presented here is novel in the environmental economics literature and makes a contribution to the understanding of the effects of regulation at firm level.

The paper is structured as follows. In Section 2 we present the pollution generating technology and develop the model for identifying which bad output is the worst. Section 3 presents the data and Section 4 the results. Finally, Section 5 provides some conclusions.

2 Methodology

In this section we first present the DEA model of a pollution generating technology, sometimes called the environmental technology, and then we develop the model for identifying which bad output is the worst based on Leif Johansen's capacity framework.

2.1 The environmental technology

Assume that the firm uses N inputs $(x_1,...,x_N) \in \Re_+^N$ to produce $M=1$ good output $y \geq 0$ and J bad outputs $(b_1,...,b_J) \in \Re_+^J$.[3] The technology represented by its output sets can then be expressed as follows.

$$P\left(x\right)=\left\{(y,b): x \text{ can produce } (y,b)\right\},\ x \in \Re_+^N \quad , \tag{1}$$

consisting of all feasible good and bad output vectors (y,b). We assume that the output sets are compact and that inputs are freely disposable, i.e., if $x' \geqq x$ then $P(x') \supseteq P(x)$. In addition, we require good and bad outputs to be jointly weakly disposable, i.e., if $(y,b) \in P(x)$ and $0 \leqq \theta \leqq 1$ then $(\theta y, \theta b) \in P(x)$, with the good output strongly disposable, i.e., if $(y,b) \in P(x)$ and $y' \leqq y$ then $(y',b) \in P(x)$. The disposability assumptions introduce the opportunity cost of reducing bad outputs in terms of reduced good output, either directly through reduced production or indirectly through re-direction of the given input bundle to abatement activities.[4] Finally, we require that good and bad outputs are null-joint: if

[3] Clearly, we may have $M>1$ desirable outputs, but here $M=1$ will suffice.

[4] This approach of modeling joint production of good and bad outputs has been challenged by Førsund (2009) and Murty et al. (2012). They suggest that the assumption of good and bad outputs being together

$(y,b)\in P(x)$ and $b=0$ then $y=0$, which means that the firm cannot produce positive quantities of good output without producing some bad output at the same time; in other words, no fire without smoke.[5] See Färe and Grosskopf (2003) for further details on the environmental technology outlined above.

To set the stage, let us recall Johansen's notion of capacity. Given that only one good output, y, is produced using two inputs $x_n \geqq 0$, $n=1,2$, capital and labor in Johansen's setting, we may define the production function as:

$$F\left(x_1,x_2\right)=\max\left\{y: y\in P(x_1,x_2)\right\}. \tag{2}$$

Johansen (1968) defines (plant) capacity as "…the maximum amount that can be produced per unit of time with the existing plant and equipment, provided that the availability of variable factors of production is not restricted (p. 50)."

Letting x_2 be the variable factor, plant capacity is given by:[6]

$$\sup_{x_2}\left\{F(x_1,x_2): x_2 \geqq 0\right\}. \tag{3}$$

Thus, with fixed x_1, and unrestricted x_2, the "largest" output determines plant capacity. The idea that one input is not restricted is here translated into each of the bad outputs.

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weakly disposable is contrary to the material balance condition. This condition basically says that what goes in, e.g., carbon input, also must come out, e.g., CO2 output (the first law of thermodynamics). Rødseth (2011) shows that weak disposability and the material balance condition both hold when allowing for abatement activities and, following the work of Rødseth, Färe et al. (2013) specify a network model with an abatement sub-technology.

[5] In the case of the air pollutants we are looking at in our analysis null-jointness is reasonable. For other types of bad outputs, such as certain types of solid waste, individual null-jointness may not always be applicable; i.e., it is possible to drive the bad output to zero without at the same time reducing good output to zero. In any case, null-jointness allows for bad outputs being zero given positive good output, as long as at least one bad output is positive.

[6] For its existence, see Färe (1984).

In this paper we construct the technology, $P(x)$, using activity analysis, or Data Envelopment Analysis (DEA). Thus, suppose there are $k=1,...K$ Decision Making Units (DMU's) and observations of inputs and outputs at each time period $t=1,...,T$. Then the output set for observation k' at t is written as:

$$P^t\left(x^t_{k'}\right)=\{(y^t,b^t):\ \sum_{k=1}^{K} z^t_k y^t_k \geqq y^t, \tag{4}$$

$$\sum_{k=1}^{K} z^t_k b^t_{kj} = b^t_j, \qquad j=1,...,J$$

$$\sum_{k=1}^{K} z^t_k x^t_{kn} \leqq x^t_{k'n}, \qquad n=1,...N$$

$$z^t_k \geqq 0, \quad k=1,\dots,K\}.$$

The equalities and inequalities justify the different disposability assumptions. Constant returns to scale is also imposed by the restriction of the intensity variables, z^t_k, being non-negative.

We require further that the data satisfies the Kemeny et al. (1956) conditions for each $t=1,...,T$, i.e.:

$$\sum_{k=1}^{K} y^t_k > 0, \tag{i}$$

$$\sum_{k=1}^{K} x^t_{kn} > 0, \quad n=1,\dots,N \tag{ii}$$

$$\sum_{n=1}^{N} x^t_{kn} > 0, \quad k=1,\dots,K \tag{iii}$$

which suffice for the output sets, $P(x)$, to be compact. Finally, following Färe and Grosskopf (2003), we impose the following conditions for each t,

$$\sum_{k=1}^{K} b_{kj}^{t} > 0, \quad j = 1, \ldots, J \tag{v}$$

$$\sum_{j=1}^{J} b_{kj}^{t} > 0, \quad k = 1, \ldots, K \tag{vi}$$

which, together with condition (i), is sufficient for good and bad outputs to be null-joint.

Having established the environmental technology, the next step is to formalize the optimization problem that helps us to identify to what extent bad outputs are restricting production of good output.

2.2 Estimating which bad output is worst

To evaluate which bad output most restricts the firms' good output production, we need to estimate to what extent a regulated bad output is restrictive in terms of production loss. This involves solving two problems. The first is to remove technical inefficiency and solve for the maximal good output that can be produced by firm k' when all bad outputs are restricted (environmentally regulated) to be at their observed values. That is, for $j = 1, ..., J$, each k', and t:

$$y_{k'}^{*t} = \max_{z_k} \; y^{t} \tag{5}$$

s.t.

$$\sum_{k=1}^{K} z_k^t y_k^t \geqq y^t$$

$$\sum_{k=1}^{K} z_k^t b_{k1}^t = b_{k'1}^t, \qquad j = 1$$

$$\sum_{k=1}^{K} z_k^t b_{kj}^t = b_{k'j}^t, \qquad j = 2, ..., J$$

$$\sum_{k=1}^{K} z_k^t x_{kn}^t \leqq x_{k'n}^t, \qquad n = 1, ..., N$$

$$z_k^t \geqq 0, \qquad k = 1, ..., K,$$

The potential relative output gain from removing inefficiency may then be expressed as the ratio of the maximal good output to the observed:

$$\frac{y_{k'}^{*t}}{y_{k'}^{t}} \geq 1, \tag{6}$$

or as a difference, $y_{k'}^{*t} - y_{k'}^{t}$. If the firm produces on the frontier of the technology set, $P(x)$, it is technically efficient and the expression in Equation (6) equals one.

The second problem is to solve for the maximal good output that can be produced by firm k' when one of the bad outputs, say b_1^t is free, i.e., not environmentally regulated to its observed value. That is, for $j = 1,..., J$, each k', and t:

$$\hat{y}_{k'}^{t}(b_1^t) = \max_{z_k} \; y^t \tag{7}$$

$$\begin{aligned}
\text{s.t.} \quad & \sum_{k=1}^{K} z_k^t y_k^t \geqq y^t \\
& \sum_{k=1}^{K} z_k^t b_{k1}^t = b_1^t, && j = 1 \\
& \sum_{k=1}^{K} z_k^t b_{kj}^t = b_{k'j}^t, && j = 2,..., J \\
& \sum_{k=1}^{K} z_k^t x_{kn}^t \leqq x_{k'n}^t, && n = 1,..., N \\
& z_k^t \geqq 0, && k = 1,..., K
\end{aligned}$$

Besides yielding the maximum output when b_1^t is unregulated, i.e., $\hat{y}_{k'}^{t}(b_1^t)$, the solution to the problem in Equation (7) also yields the optimal bad output value, $\hat{b}_1^t$.

The main purpose of this paper is to determine which bad output is worst in terms of loss of production. This will be possible by comparing $\hat{y}_{k'}^{t}(b_1^t)$ (where one bad is unregulated) and $y_{k'}^{*t}$ (where all bads are regulated). For example, $\forall t$ and $\forall k'$:

$$\frac{\hat{y}_{k'}^{t}(b_1^t) - y_{k'}^{*t}}{y_{k'}^{*t}} \cdot 100 \tag{8}$$

tells us by what percent firm k' can increase good output production if the bad output b_1^t is not regulated. In a similar manner, to evaluate the impact of policy on emissions, we can calculate the percent by which firms could increase bad outputs if it were not being regulated.

3 Data

To estimate the environmental technology and the restrictiveness of bad outputs we make use of Swedish manufacturing firm level data especially compiled for our research by Statistics Sweden (www.scb.se).[7] However, in this paper we focus particularly on the pulp and paper industry, using data covering the period 1990 to 2008. The data cover nearly the whole population. The pulp and paper industry is highly relevant in the context of environmental policy as it is subjected to regulation on all three of the pollutants we are focusing on in the analysis.

The firms produce one good output and this variable is created by dividing firm level sales by a sector level producer price index, which serve as a proxy for physical output (an output index). At the same time, bad outputs, in our case carbon dioxide (CO_2), sulfur dioxide (SO_2), and nitrogen oxides (NO_X), are produced as by-products (air pollutants, measured in tons). Inputs used in production are real capital (machines and buildings), measured in million SEK,[8] number of employees, fossil fuels (coal, oil, gasoline) and non-fossil fuels (electricity,[9] biofuels, heat), where energy inputs are measured in MWh. By separating fossil fuels and non-fossil fuels we do not need to assume these types of fuels to be perfect substitutes. The data for all variables used in the empirical application are summarized in Table 1.

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[7] This is the same data as used in Färe et al. (2012a, 2012b).

[8] The capital stock is created from firm level data on gross investment by using the perpetual inventory method (for details, see Färe et al., 2012a).

[9] In Sweden electricity is produced mainly by using non-fossil intensive technologies, mainly hydro and nuclear power.

Table 1: Descriptive statistics, the Swedish pulp and paper industry data in 1990 and 2008 (2008 prices).

Variables	Units	Mean	SD	Minimum	Maximum
		1990 (number of firms=92)			
Good output	MSEK	793.1	1677.0	11.5	13687.5
CO2	ton	11977.4	24434.0	3.0	140042.7
SO2	ton	20.8	47.0	0.0	273.5
NOx	ton	22.9	52.6	0.0	315.2
Capital	MSEK	417.4	920.7	0.3	5200.3
Labor	Workers	553.1	1144.6	17.0	9739.0
Fossil fuels	MWh	43287.1	87542.1	12.8	510640.2
Non-fossil fuels	MWh	196586.9	461482.0	173.0	2826444.5
		2008 (number of firms=84)			
Good output	MSEK	1005.9	1670.7	7.6	10870.7
CO2	ton	15752.1	29579.3	0.8	168367.5
SO2	ton	24.2	48.2	0.0	275.5
NOx	ton	47.0	88.8	0.0	459.5
Capital	MSEK	807.3	1452.0	0.4	6811.6
Labor	Workers	324.3	479.9	9.0	3490.0
Fossil fuels	MWh	58794.5	108928.0	3.0	616247.1
Non-fossil fuels	MWh	397358.5	838584.1	120.0	5485764.0

The average production of good output among the firms in the data set is nearly 30 percent larger in 2008 than in 1990. Capital use in production is approximately 90 percent higher and labor about 40 percent lower. This indicates a considerable increase in capital intensity. The average energy use is also considerably higher in 2008 as non-fossil fuel use is about 100 percent higher than in 1990, and fossil fuel use is about 35 percent higher. One would expect increasing air emissions with increasing use of energy, which is confirmed by the data. Emissions of CO2, SO2, and NOx are about 30, 15, and 100 percent higher in 2008, respectively. By means of an index (base year 1990 =100), Figure 1 illustrates the pattern of emissions during the sample period (1990 to 2008) for Swedish Pulp and paper firms, e.g., in the CO2 case, $\sum_{k=1}^{K} CO2^{kt} \Big/ \sum_{k=1}^{K} CO2^{k,1990}$.

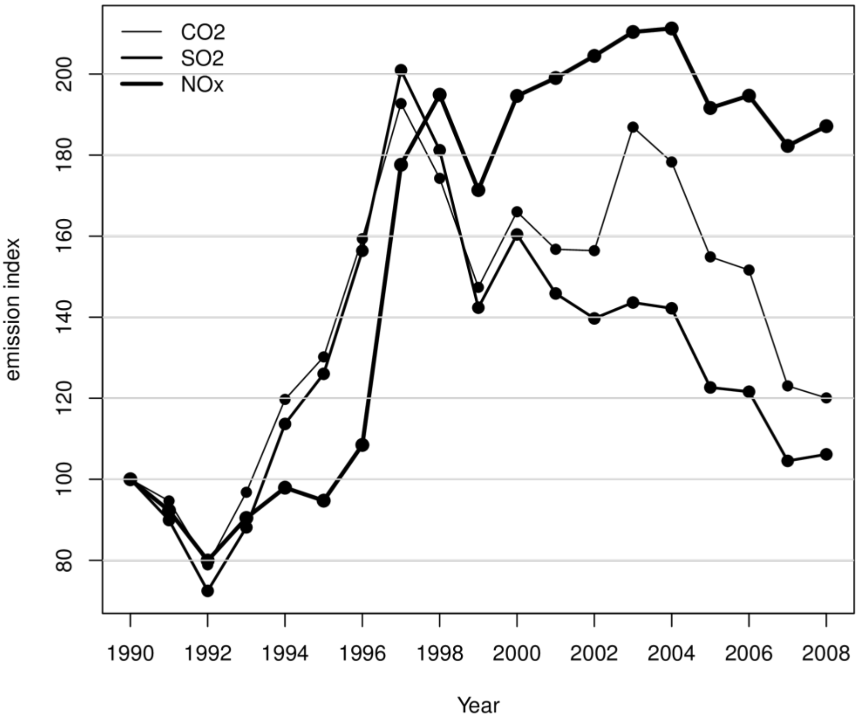

Figure 1. Emissions of CO2, SO2, and NOx between 1990 and 2008.
Index, 1990=100.

Even though emissions are considerable larger in 2008 compared to 1990, they are considerable smaller compared to, e.g., 2004. The sharp increase in emissions in the years before 1997 can partially be explained by the recovery from the deep recession that started 1992 (monetary crisis in Sweden). One reason for the distinctive increase in NOx emissions is the substantial increase in non-fossil fuels as input in production compared to the increase in fossil fuels. NOx is generated both from non-fossil and fossil fuel use, while CO2 stem only from fossil fuels and SO2 mainly from fossil fuels.[10]

[10] That CO2 emissions only stem from fossil fuel use is due to the assumption that non-fossil fuels, e.g., biofuels, are carbon neutral (this is the prevailing assumption when the emissions are estimated by Statistics

The overall trend is increasing emissions from the early 1990s to1997. CO_2 and SO_2 emissions have generally decreased ever since. However, NO_x emissions were slightly larger in 2008 compared to 1997.

4 Results

Following Färe et al. (2012a), we argue that the production technology could be modeled as an environmental technology, which accounts for bad outputs being produced simultaneously with the marketable good output. The environmental technology is theoretically characterized by the properties of output disposability and null-jointness, as proposed by Färe et al. (1986). Empirically we study to what extent Swedish pulp and paper firms are restricted by bad outputs subject to environmental regulation. Based on Equation (8), which gives the percent by which output would increase if the associated bad were not regulated, Figure 2 shows the pattern of the potential output gains in the 1990 to 2008 period, explicitly $\{\sum_{k=1}^{K}\hat{y}_{k'}(b_1)-\sum_{k=1}^{K}y_{k'}^{*t})\Big/\sum_{k=1}^{K}y_{k'}^{*t}\}\cdot 100$, where $\hat{y}(b_1)$ indicates that CO_2, SO_2, or NO_x is not regulated.

Sweden). However, treating biofuels carbon neutral is sometimes referred to as a “carbon accounting error”, see, e.g., Lundgren and Marklund (2012a, 2012b), Haberl et al. (2012), Cherubini et al. (2011), and Searchinger et al. (2009), for a discussion.

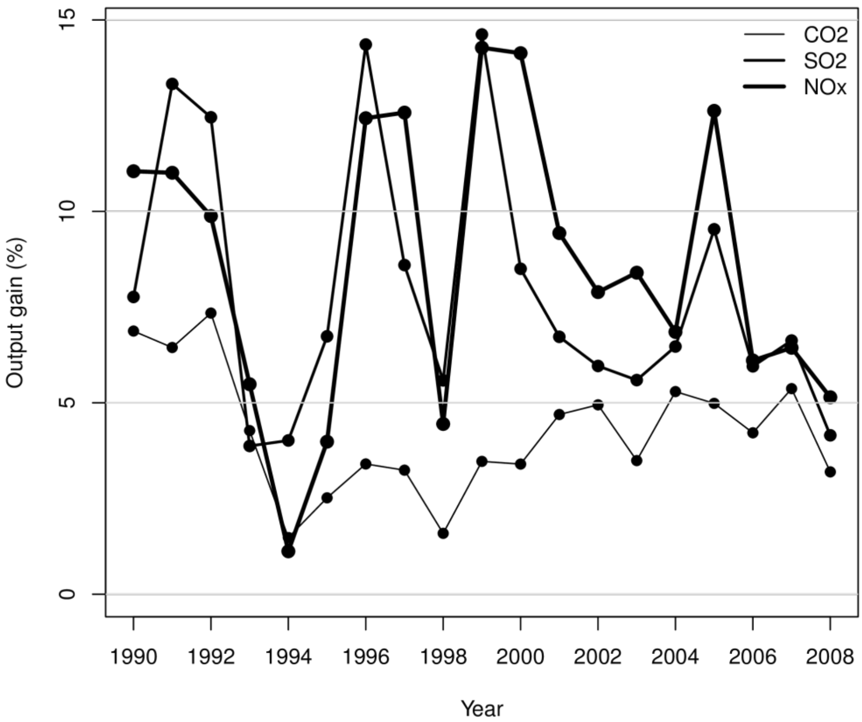

Figure 2. Potential good output gain in percentage if one bad output, CO2, SO2, or NOx, had not been regulated (see Equation (8)).

To some extent the results seem to reflect the history of environmental policy in Sweden. In 1990-1991 a major tax reform was implemented. The reform, covering the whole tax system, introduced taxes on CO2 and SO2 emissions, and a fee on NOx emissions in combustion plants (see Brännlund, 2009, for a detailed discussion).[11] In 1991 the CO2 tax rate was set to SEK 0.25 per kilo emitted (Swedish Energy Agency, 2006). The sulfur tax rate was set to SEK 30 per kilo of sulfur emissions from coal and peat, as well as to SEK 27 per m3 for each tenth of weight percentage sulfur content in oil (Swedish Energy Agency, 2008). These sulfur tax rates were still valid in 2008. A fee of SEK 40 per kilo NOx emissions was introduced in 1992 (Swedish Environmental Protection Agency, 2003), and in January 1 2008 it was increased to SEK 50 per kilo (Swedish Energy Agency, 2008).

[11] See also Brännlund et al. (2011) for an empirical evaluation of the Swedish CO2 tax scheme and its impact on firms' environmental performance.

As Figure 2 illustrates, in 1991 the firms in the sample display large foregone production when we simulate deregulating individual bads, especially in the case of SO_2. In 1991 production of good output could have been increased about 13 percent if SO_2 had not been regulated. In 1993 an energy tax reform was implemented, which substantially increased energy and CO_2 tax rates for the households. However, the energy tax reform also implied that the manufacturing sector was exempted from energy taxes on fuels and electricity used in the production process, and only taxed at 25 percent of the new statutory CO_2 tax rate. As shown in Figure 2, the pulp and paper firms in the data exhibits smaller potential output gains when we simulate deregulation of bads in 1993 and the following year. For instance, in 1994 the firms could have increased production of good output by about 4 percent if SO_2 had not been regulated. Compared to 1994 the pulp and paper firms perceived the production being more restricted by bad outputs in the second half of the 1990s, especially in 1999. In the CO_2 case one contributory cause may be that in 1997 the CO_2 tax was considerably increased for the manufacturing sector as the tax exemption was reduced to 50 percent of the CO_2 tax rate (Statistics Sweden, 2000). However, in 2001 the exemption was adjusted so that the effective CO_2 tax rate paid by the manufacturing sector became unaffected by increases in the statutory tax rate (Lewin, 2009).[12] Additionally, in 2004 the manufacturing sector's exemption from the energy tax on electricity was abolished and replaced by an energy tax rate equal to SEK 0.005 per KWh (Lewin, 2009). Figure 2 shows that from 2001 and onwards the pulp and paper firms exhibit smaller opportunity costs (i.e. losses in potential output) of regulation of bad outputs relative to 1991 (except for NO_x in 2005), i.e., the early days of the major tax reform.

A general conclusion drawn from Figure 2 is that during the period of study, CO_2 regulation appears to restrict potential output the least for the pulp and paper firms. This is reasonable as in 2008 only 31 firms out of 84 in the data paid CO_2 tax. Until 1999 SO_2 tended to be the most restrictive bad output, and after 1999 this was NO_x.

To bring further information we particularly look into year 2008. The Salter Diagrams in Figure 3 show that individual firms experience the restrictiveness of bad outputs to a considerably varying degree. The potential output gain (Equation (8)) that could have been

[12] The CO_2 tax rate increase was substantial the first half of the 2000s, from SEK 0.37 in 2000 to SEK 0.91 in 2004, i.e., a 146 percent increase (Swedish Energy Agency, 2006). After 2004 the CO_2 tax rate was stepwise increased and in 2008 it was SEK 1.01. This stepwise increase mainly burdened the households.

achieved in 2008 if the bad output had not been restricted by environmental regulation, is measured on the vertical axes in Figure 3. [13] On the horizontal axes the width of the columns illustrates the size of the individual firms as measured by the proportion of total sector good output. The amount of zero value firms are also indicated in the figures.

[13] Detailed information about the output quantities can be obtained from the authors upon request.

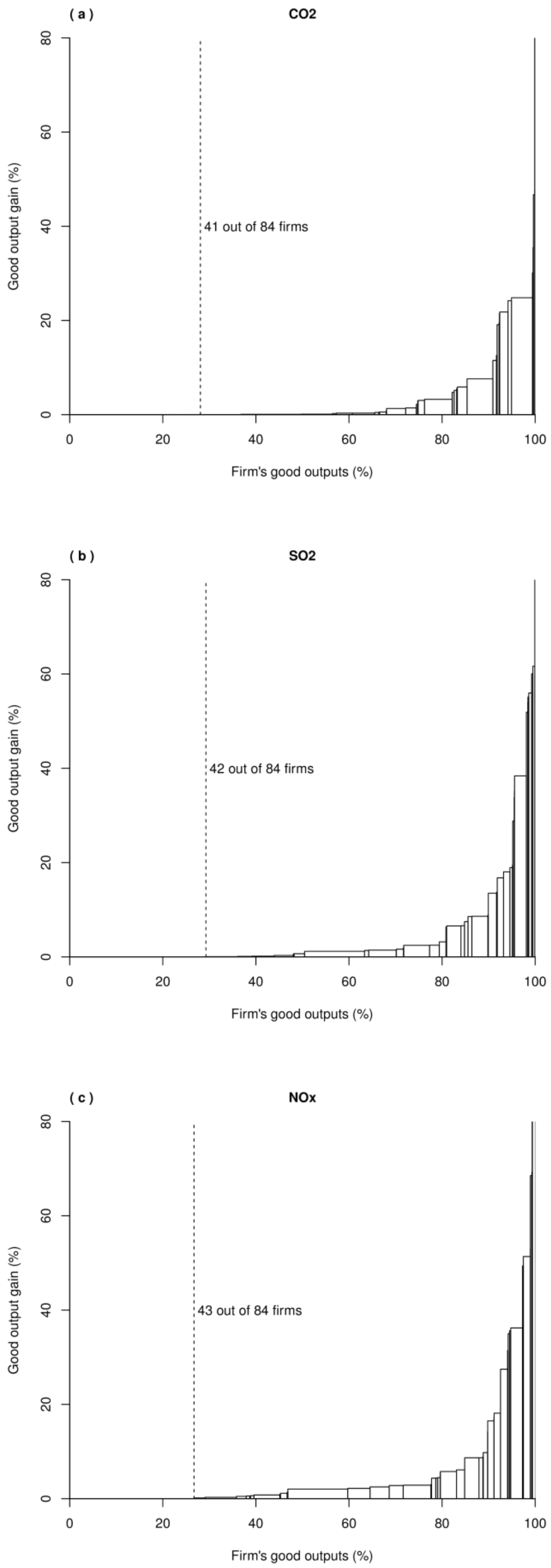

Figure 3. Good output gain if Impact of environmental regulation – The firm level

Figure 3a shows the result from the effect of CO_2 being regulated. Far from all firms were adversely affected as only 41 firms out of 84 could have increased production of good output if CO_2 had not been regulated. These firms produced more than 70 percent of the good output totally produced, which indicates that firms that were restricted are larger on average than those that were not. Similar conclusions can be drawn from Figures 3b and 3c, when explicitly studying SO_2 and NO_x, respectively.

As mentioned above the model outlined in the previous section can also be used to calculate the percent by which firms could increase a certain bad output if it were not being regulated. However, inherent in the DEA approach used is the potential of some firms being observed operating far out to the left of the output possibility set, expressed in Equation (1). If so, the observed regulated bad output quantities will be larger than the optimal non-regulated bad output quantities, which make little economic sense. In our estimations we can observe this, especially in the CO_2 case. The cause of this problem may be related to the fact that firms in the data are too heterogeneous in energy use, and therefore also in emissions, causing problems in the DEA optimization. Other contributing factors could be data inconsistencies, or possibly strong positive correlation among the bad outputs. The empirical application should therefore only be considered as an illustration of which type of results that can be generated by the model we suggest. We are experiencing some problems possible reinforced by the interaction between inherent properties of the DEA approach and the data.

5 Conclusions

Industrial production causes emissions of undesirables that generate negative externalities. From the societal point of view it is therefore of interest to implement environmental policy measures and regulate firms emissions, or bad outputs. Regulating bad outputs may restrict firms' in terms of forgone production of desirable outputs, or good outputs. The purpose of this paper has been to develop a model to identify which bad is worst, i.e., the bad output that due to regulation most restricts firms' production of good outputs. This model may therefore be used as an instrument to assess environmental regulation, e.g., by ranking the restriction of different types of bad outputs being subject to different tax rates. The model developed is an application of Leif Johansen's capacity framework, and resembles what is referred to as von Liebig's Law of the Minimum.

To illustrate the model we apply it to Swedish pulp and paper data at the firm level, covering the period 1990 to 2008. The pollution generating technology explicitly modeled, where good and bad outputs are produced simultaneously, exhibits the properties of disposability and null-jointness as proposed by Färe et al. (1986). To solve which bad is the worst, or causes firms the largest adjustment costs, we use a Data Envelopment Analysis (DEA) approach.

The result generally shows that CO2 was the least restrictive bad output in terms of causing forgone production of good output due to regulation. From a policy point of view this indicates there was a potential for raising the CO2 tax without inflicting too much costs (relative to the cost of regulating other bads) on the firms. As CO2, SO2, and NOx seem highly correlated, this would also have contributed to further reduction of SO2 and NOx at a lower cost compared to regulating these emissions directly more stringently.

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