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Interfaces with Other Disciplines

Environmental efficiency, irreversibility and the shadow price of emissions[☆]Elvira Silva^a, Manuela Magalhães^{b,*}^a Faculty of Economics & Center for Economics and Finance, University of Porto, Porto, PT, Portugal^b Department of Economic Theory and Economic History, University of Málaga, Spain, and CEFAGE, Portugal

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ABSTRACT

Assessing the production of goods and services while minimizing the damage to the environment is a key component to advance sustainable development at national and global levels. The nonparametric estimation of lower and upper bounds on shadow prices of pollutants is undertaken to support the design of policies promoting environmental efficiency in the presence of asymmetry in adjusting productive and abatement capital capacity. This framework is applied to the pulp and paper sector of 39 countries for 1996–2009, and finds that the USA, China and Ireland are the most environmentally inefficient countries in the pulp and paper sector. The adjustment costs associated with net investment and disinvestment are found to be asymmetric. For those nations where the shadow price of CO₂ is lower than the carbon tax, there is still an opportunity to abate emissions further. Results on complementarity or substitutability between pollutants are in general inconclusive.

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1. Introduction

Ensuring environmental sustainability is a key aim of international initiatives to meet “the needs of the present without compromising the ability of future generations to meet their own needs” (World Business Council for Sustainability, 2000). Part of this challenge is to develop mechanisms to manage the negative impacts of economic activity that can compromise environmental sustainability going forward. The environment can no longer be treated as a free input. A consequence of many manufacturing activities is the concomitant production of undesirable byproducts [emissions and pollutants] whose cost is not borne by those economic agents responsible for their generation. The core of production decision making involves what to produce in terms of both desirable and undesirable outputs, how much to produce, and how to produce. While economic instruments such as marketable permits and taxes have emerged as policy approaches to manage these negative spillovers, a first step is estimating the value, or shadow price, for these non-marketed economic damages. The regulatory environment encourages the installation of new capital to

address the emissions and pollution abatement, and consequently, promote sustainable production.

Environmental efficiency and shadow pricing of emissions are the aim of many of studies in recent decades. Environmental efficiency refers to the ability of firms, industries or economies to produce goods and services while incurring less impact on the environment, and has gained increasing attention due to concerns about environmental quality and (economic and social) sustainable development at the global level (Rødseth, 2014; Halkos and Tzeremes, 2014; Picazo-Tadeo et al., 2012; Färe et al., 2005; Färe et al., 2006; Korhonen and Luptacik, 2004).

The shadow price of emissions provides important information to implement environmental policies and is the aim of several theoretical and empirical studies (Podinovski, 2019; Podinovski et al., 2016; Kuosmanen et al., 2010; Lee et al., 2002; Reig-Martinez et al., 2001). In particular, these shadow prices can serve as weights in the estimation of the environmental damage function used in the construction of eco-efficiency measures (Picazo-Tadeo et al., 2011; Kortelainen & Kuosmanen, 2007; Kuosmanen & Kortelainen, 2005). Zhou et al. (2014) present a review of the shadow price estimation of undesirable outputs in the literature, using parametric and non-parametric methods.

A series of studies (e.g., Podinovski, 2019; Førsund, 2018; Podinovski et al., 2016) discuss the non-uniqueness of the shadow prices at the extreme-efficient units (i.e., vertex points of the

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frontier) when non-parametric production frontier methods are employed. Podinovski (2019) applies the unifying approach in Podinovski et al. (2016) to the case of undesirable outputs and show how to evaluate the one-sided directional derivatives of the directional distance function at the extreme-efficient units.

Environmental performance studies, in general, focus on static models of production which neglect the effects of intertemporal tradeoffs associated with the time interdependence of production and investment decisions. In a manufacturing setting, the capital stock embodies the production technology's potential to mitigate the undesirable byproducts. This investment in both productive and abatement capital can be specific to the firm and is a sunk cost. Further, the evolving regulatory setting and consumer attitudes toward firms' impact on the environment can lead to demand uncertainty for their products. The presence of irreversibility and the potential for demand uncertainty suggest the "real option" context for decision making (Dixit & Pindyck, 1994; Nicolai, 2019). Wiersma (1991) and Bostian et al. (2016) are among the few studies that introduce dynamic aspects of production in addressing environmental efficiency modelling.

Transaction costs, inventories, production delays, among others, are factors of intertemporal dependence of production decisions that are addressed in the dynamic efficiency literature. Fallah-Fini et al. (2014) offer an extensive review on non-parametric dynamic efficiency measurement. Among these time-dependent factors, several efficiency studies employ the adjustment cost framework for investment decision making which is associated with changes in the capital stock level (Nemoto & Goto, 2003; Silva & Stefanou, 2003, 2007; Kao, 2013; Chen & van Dalen, 2010; Silva et al., 2015). Adjustment costs are typically associated with the installation of new capital, and may be viewed as output-reducing costs as resources from production are diverted to support investment. This leads to the core of the dynamic resource allocation problem involving the trade-off between current production and future production potential (Lucas 1967; Treadway 1970; Rothschild 1971; Mortensen 1973).

This study constructs a production theoretic framework allowing for investment in both productive and pollution abatement capital that can address the implicit valuation of undesirable outputs and identify the tradeoffs in emission reductions. Adjustment costs may reduce the impact of environmental policy. The higher the adjustment costs, the smaller the changes in productive and abatement inputs from a change in emission taxes (Xepapadeas, 1992).

A case in point is the pulp and paper sector, which is a major generator of emissions as a production byproduct. The emissions in this study are carbon dioxide (CO₂), nitrous oxide (N₂O) and sulfur oxides (SO_x). This sector serves as a compelling case to address environmental efficiency and shadow value pricing for regulatory purposes. The fourth largest industrial emitter of GHG at the global level, this sector is energy- and raw materials-intensive and characterized by considerable investment irreversibility due to significant sunk capital costs and demand uncertainty (Maynard & Shortle, 2001; Droege, 2013). Empirical studies focusing on environmental issues and the shadow price of emissions in the pulp and paper sector include Färe et al. (1989), Färe et al. (1993), Chung et al. (1997), Brännlund et al. (1998), Hailu and Veeman (2000, 2001), Gary et al. (2014), Akpan et al. (2015), and Elrod and Malik (2017). These studies are conducted in a setting with no intertemporal trade-offs and, in general, using plant- or industry-level data in a particular country.

The remainder of this study is organized as follows. The next section presents the methodological framework measuring environmental performance using the output-oriented directional distance function implemented by Data Envelopment Analysis (DEA), and generating the shadow pricing of emissions, of invest-

ment/disinvestment, as well as the marginal rate of transformation between emissions using the approach in Podinovski (2019). This is followed by the description the data, then the empirical results and their policy implications are discussed. The final section presents concluding remarks.

2. Methodology

Several studies consider abatement capital as a defensive expenditure, which can be distinguished from productive capital by differences in the costs associated with installation, training and learning, and other transactions costs (Harford, 1976; Beavis, 1979; Xepapadeas, 1992). Building on the foundation of the adjustment-cost theory of the firm (Lucas, 1967; Treadway, 1970; Rothschild, 1971), Silva and Stefanou (2003, 2007) and Silva et al. (2015) develop the DEA framework that can operationally incorporate a dynamic production technology. When addressing both the desirable and undesirable outputs, the flexibility of a directional multi-output distance function presents a viable framework to represent environmental inefficiency (Chung et al, 1997; Silva et al, 2015).

Studies addressing dynamic adjustment impose the total irreversibility of investment on the gross investment vector (also called the vector of dynamic factors) $I \in \mathbb{R}_+^F$, where F represents the number of quasi-fixed factors used by the firm. We relax this constraint to allow $\dot{K} = (\dot{K}^+, \dot{K}^-)$ where $\dot{K} = I - \delta K$, δ is the depreciation rate and $K \in \mathbb{R}_+^F$ is the capital stock vector. \dot{K}^+ is the vector of net investment and \dot{K}^- the vector of net disinvestment, which eliminates total irreversibility and allows the possibility of asymmetric adjustment costs.

Let $\dot{K} \in \mathbb{R}^F$, $\dot{K}^+ \in \mathbb{R}_+^{F^+}$, $\dot{K}^- \in \mathbb{R}_+^{F^-}$ and $F = F^+ \cup F^-$, where F^+ is the number of quasi-fixed factors with net investments and F^- represents the number of quasi-fixed factors with net disinvestment. Let also $x \in \mathbb{R}_+^N$ be the variable input vector, $y \in \mathbb{R}_+^M$ the (good) output vector and $E \in \mathbb{R}_+^B$ the emissions vector. The adjustment-cost production technology is represented by the following directional output distance function,

$$\begin{aligned} \bar{D}_O : \mathbb{R}_+^N \times \mathbb{R}_+^F \times \mathbb{R}_+^{F^+} \times \mathbb{R}_+^{F^-} \times \mathbb{R}_+^M \times \mathbb{R}_+^B \times \mathbb{R}_+^M \times \mathbb{R}_+^B &\rightarrow \mathbb{R}, g = \\ (g_y, g_E) \in \mathbb{R}_+^M \times \mathbb{R}_+^B, g \neq 0_{M+B}, &\text{ defined as} \\ \bar{D}_O(x, K, \dot{K}^+, |\dot{K}^-|, y, E; g_y, g_E) & \\ = \max \{ \beta \in \mathbb{R} : (y + \beta g_y, E - \beta g_E) \in P(x, \dot{K}^+, |\dot{K}^-|; K) \}, & \end{aligned} \quad (1)$$

where $P(x, \dot{K}^+, |\dot{K}^-|; K)$ is the output set. The properties of the directional output distance function in (1) and the regularity conditions of the output set are presented in Appendix A.

Consider a data series $\{(y_t^j, x_t^j, K_t^j, \dot{K}_t^{+j}, \dot{K}_t^{-j}, E_t^j), j = 1, \dots, J; t = 1, \dots, T\}$ representing the observed behavior of each firm j at time t . The DEA model corresponding to (1), given properties P1-P7 of the output set in Appendix A and the previous data series, can be defined as¹

$$\begin{aligned} \max_{\beta, z} \{ \beta : \sum_{j=1}^J z^j y_m^j \geq y_m^i + \beta g_{y_m}, m = 1, \dots, M; \\ \sum_{j=1}^J z^j E_b^j = E_b^i - \beta g_{E_b}, b = 1, \dots, B; \sum_{j=1}^J z^j x_n^j \leq x_n^i, n = 1, \dots, N; \\ \sum_{j=1}^J z^j \dot{K}_f^{+j} \geq \dot{K}_f^{+i}, f \in F^+; \sum_{j=1}^J z^j |\dot{K}_f^{-j}| \geq |\dot{K}_f^{-i}|, \\ f \in F^-; z^j \geq 0, j = 1, \dots, J \}; \end{aligned} \quad (2)$$

where z is the vector of intensity variables. This model provides simultaneously the maximum possible expansion of the good output vector and the maximum possible contraction of emissions for each observation i along the direction g , given $x^i, \dot{K}^{+i}, \dot{K}^{-i}$ and

¹ The time index t is suppressed, in this model and the primal and dual models that follow, for the sake of clearer exposition.

K^i . The optimal value of (2) provides a measure of environmental efficiency. The context of this problem maintains a technology where an increase in the good output can only be realized with an increase in emissions (the bad output). The marginal rate of transformation between good and bad outputs can be positive or negative.²

The shadow prices of emissions and of investment/disinvestment are generated following the approach proposed in Podinovski (2019), which is an extension of the work by Podinovski et al. (2016). In order to generate the shadow prices of emissions for firm i , consider the following directional response function:

$$\bar{\beta}(\gamma) = \max \{ \beta : (X^i, K^i, \dot{K}^{+i}, |\dot{K}^{-i}|, Y^i + \beta g_y, E_b^i + \gamma g_E) \in P(X^i, \dot{K}^{+i}, |\dot{K}^{-i}| : K^i) \} \quad (3)$$

The function in (3) is a directional distance functions as in (1) defined by the direction g_y , for all units $(X^i, K^i, |\dot{K}^{si}|, Y^i, E^i)$, $s=+,-$, by the parameterized perturbation γg_E . The DEA model corresponding to (3) is as follows, for $b'=1, \dots, B$, and $m'=1, \dots, M$:

$$\begin{aligned} \max_{\beta, z} \{ \bar{\beta}_{b'}(\gamma) : & - \sum_{j=1}^J z^j y_{m'}^j + \beta g_{y_{m'}} \leq -y_{m'}^i; \\ & - \sum_{j=1}^J z^j y_m^j \leq -y_m^i \quad m \neq m'; \quad - \sum_{j=1}^J z^j \dot{K}_f^{+j} \leq -\dot{K}_f^{+i}, \quad f \in F^+; \\ & - \sum_{j=1}^J z^j |\dot{K}_f^{-j}| \leq -|\dot{K}_f^{-i}|, \quad f \in F^-; \quad \sum_{j=1}^J z^j E_{b'}^j = E_b^i + \gamma g_{E_b}; \\ & \sum_{j=1}^J z^j E_b^j = E_b^i; \quad b \neq b'; \quad \sum_{j=1}^J z^j x_n^j \leq x_n^i, \\ & n = 1, \dots, N; \quad -\beta g_{y_{m'}} \leq y_{m'}^i; \quad z^j \geq 0, \quad j = 1, \dots, J \}. \end{aligned} \quad (4)$$

The directional vectors $g_{y_{m'}} = g_{E_b} = 1$ and the last but one constraint in (4) is a non-negativity constraint. The non-negativity of the term $y_{m'}^i + \beta g_{y_{m'}}$ does not follow from the first constraint in (4) and is introduced in the last but one constraint (Podinovski, 2019). Let Γ be the domain of the function $\bar{\beta}_{b'}(\gamma)$, that is the set of all values γ for which the optimization problem in (4) is feasible and has a finite optimal value. Given Γ is a closed interval and $\bar{\beta}_{b'}(\gamma)$ is a continuous, concave and piecewise linear function (Proposition 2 in Podinovski et al (2016)), the function $\bar{\beta}_{b'}(\gamma)$ has a finite right-hand (left-hand) derivative at any γ that is not the right (left) extreme point of Γ (Podinovski et al., (2016)).

Consider the dual to (4) with $\gamma=0$:

$$\begin{aligned} \min_{\lambda^x, \lambda^y, \lambda^E, \lambda^+, \lambda^-} \{ & \sum_{n=1}^N \lambda_n^x x_n^i - \sum_{f \in F^+} \lambda_f^+ \dot{K}_f^{+i} - \sum_{f \in F^-} \lambda_f^- |\dot{K}_f^{-i}| \\ & + \sum_{b=1}^B \lambda_b^E E_b^i - \sum_{m=1}^M \lambda_m^y y_m^i : 1 - \lambda_{m'}^y = 0; \sum_{m=1}^M \lambda_m^y y_m^j - \\ & \sum_{b=1}^B \lambda_b^E E_b^j - \sum_{n=1}^N \lambda_n^x x_n^j + \sum_{f \in F^+} \lambda_f^+ \dot{K}_f^{+j} + \sum_{f \in F^-} \lambda_f^- |\dot{K}_f^{-j}| \\ & \leq 0, \quad j = 1, \dots, J; \quad \lambda_n^x, \lambda_m^y, \lambda_f^+, \lambda_f^- \geq 0, \quad \lambda_b^E \text{ free sign} \}. \end{aligned} \quad (5)$$

The dual variables λ_n^x , λ_m^y and λ_b^E are the current value of the Lagrangian multipliers associated with the variable input constraint, the output constraint and the emissions constraint in (4), respectively. Using the Envelope Theorem, λ_n^x and $-\lambda_m^y$ are the shadow prices, respectively, of the variable input x_n^i and output y_m^i , and λ_b^E is the shadow price of emissions E_b^i . The dual variable

² Murty et al (2012) critique the weak disposability of bad outputs for not necessarily being consistent for technologies that permit no trade-off between the good and bad outputs; specifically, when good output can be realized with zero bad output. For example, Chambers et al (2014) focus on the overuse of an input creating a residual that creates a bad output as a by-product.

λ_f^+ (λ_f^-) is the current value of the Lagrangian multiplier associated with the constraint on net investment (disinvestment) of the quasi-fixed factor $f \in F^+$ ($f \in F^-$). Using the Envelope Theorem, $-\lambda_f^+$ and $-\lambda_f^-$ are the shadow prices, respectively of \dot{K}_f^{+i} and $|\dot{K}_f^{-i}|$, which are interpreted as the marginal adjustment cost of investment and disinvestment (Ouellette & Yang, 2008; Silva et al., 2015). By introducing investment and disinvestment restrictions in (4), we allow for asymmetry by not imposing that the marginal adjustment cost of investment, $-\lambda_f^+$, is equal to the marginal cost of disinvestment, $-\lambda_f^-$.

The objective function in (5) can be interpreted as the current shadow variable profit. The algebraic sum of the first three components corresponds to current shadow variable costs, with the following components: the current shadow value of variable inputs, $\sum_n \lambda_n^x x_n^i$, plus the current shadow value of net investment, $-\sum_{f \in F^+} \lambda_f^+ \dot{K}_f^{+i}$ and of net disinvestment, $-\sum_{f \in F^-} \lambda_f^- |\dot{K}_f^{-i}|$. The last two components are, respectively the current shadow value of emissions, $\sum_b \lambda_b^E E_b^i$ and the current shadow value of the good outputs, $-\sum_m \lambda_m^y y_m^i$.

Following Podinovski (2019), the left-hand directional derivative $\bar{\beta}'_{b'-}(0)$ is the optimal value of the following maximization program:

$$\begin{aligned} \bar{\beta}'_{b'-}(0) = \max \{ & \lambda_{b'}^E : 1 - \lambda_{m'}^y = 0; \\ & \sum_{n=1}^N \lambda_n^x x_n^i - \sum_{f \in F^+} \lambda_f^+ \dot{K}_f^{+i} - \sum_{f \in F^-} \lambda_f^- |\dot{K}_f^{-i}| + \sum_{b=1}^B \lambda_b^E E_b^i - \sum_{m=1}^M \lambda_m^y y_m^i = \bar{\beta}(0); \\ & \sum_{m=1}^M \lambda_m^y y_m^j - \sum_{b=1}^B \lambda_b^E E_b^j - \sum_{n=1}^N \lambda_n^x x_n^j + \sum_{f \in F^+} \lambda_f^+ \dot{K}_f^{+j} + \sum_{f \in F^-} \lambda_f^- |\dot{K}_f^{-j}| \leq 0, \\ & j = 1, \dots, J; \quad \lambda_n^x, \lambda_m^y, \lambda_f^+, \lambda_f^- \geq 0, \quad \lambda_b^E \text{ free sign} \}. \end{aligned} \quad (6)$$

The right-hand directional derivative $\bar{\beta}'_{b'+}(0)$ is found as the optimal value of the following minimization program:

$$\begin{aligned} \bar{\beta}'_{b'+}(0) = \min \{ & \lambda_{b'}^E : 1 - \lambda_{m'}^y = 0; \\ & \sum_{n=1}^N \lambda_n^x x_n^i - \sum_{f \in F^+} \lambda_f^+ \dot{K}_f^{+i} - \sum_{f \in F^-} \lambda_f^- |\dot{K}_f^{-i}| + \sum_{b=1}^B \lambda_b^E E_b^i - \sum_{m=1}^M \lambda_m^y y_m^i = \bar{\beta}(0); \\ & \sum_{m=1}^M \lambda_m^y y_m^j - \sum_{b=1}^B \lambda_b^E E_b^j - \sum_{n=1}^N \lambda_n^x x_n^j + \sum_{f \in F^+} \lambda_f^+ \dot{K}_f^{+j} + \sum_{f \in F^-} \lambda_f^- |\dot{K}_f^{-j}| \leq 0, \quad j = 1, \dots, J; \\ & \lambda_n^x, \lambda_m^y, \lambda_f^+, \lambda_f^- \geq 0, \quad \lambda_b^E \text{ free sign} \}. \end{aligned} \quad (7)$$

$\bar{\beta}'_{b'-}(0)$ ($\bar{\beta}'_{b'+}(0)$) in (6) ((7)) is the left-hand (right-hand) shadow price of emissions and $\bar{\beta}(0)$ is the value of the objective function in (5). Both $\bar{\beta}'_{b'-}(0)$ and $\bar{\beta}'_{b'+}(0)$ are evaluated on the production frontier. For inefficient observations (i.e., $\bar{\beta}(0) > 0$), the left- and the right-hand shadow prices are evaluated at the projection of the observation on the production frontier in the direction of maximization of the good output $y_{m'}$, as required by the first constraint in (6) and (7) (Podinovski (2019), Podinovski et al (2016)). If $\gamma=0$ is the left (right) extreme point of Γ , then the optimal value program (6) ((7)) is unbounded (Theorem 1 in Podinovski (2019)). Given that $\bar{\beta}(\gamma)$ is a continuous, concave and piecewise linear function, if $\gamma=0$ is an interior point of Γ , then $\bar{\beta}'_{b'+}(0) \leq \bar{\beta}'_{b'-}(0)$ (Podinovski, 2019; Podinovski et al., 2016).

The one-sided marginal rate of transformation between two bad outputs is also estimated using the approach proposed in Podinovski (2019). Please see Appendix B. The shadow prices of investment/disinvestment are generated in a similar way as the shadow prices of emissions. Please see Appendix C.

3. Data

Our primary data source is the publicly accessible World Input-Output Database (WIOD), based on national accounts and developed within the Seventh Framework Program of the European Commission (see [Timmer et al. \(2015\)](#) for additional details). In addition to bilateral trade data, the WIOD also includes data on labor and capital inputs (the Social Economic Accounts), and pollution indicators (the Environmental Accounts) at the industry level.

The WIOD covers 39 countries, including all 27 European Union countries and 12 other major countries (Australia, Brazil, Canada, China, India, Indonesia, Japan, Mexico, Russia, South Korea, Turkey and the USA) in the time period 1995–2009.³ This database has the advantage of using a set of harmonized procedures ensuring international comparability and includes sectoral price deflators providing important information about the heterogeneity of the sectors.

The pulp and paper sector comprises pulp, paper, paper products, printing and publishing products. The industry output used is gross output (GO) which is expressed in millions of each country's currency. The variable input used is labor (millions of total hours worked) and energy that consists of fuel (diesel, gasoline and oil) (terajoules).⁴ Capital is the quasi-fixed factor, measured in millions of each country's currency. The annual net investment/disinvestment is computed by the difference of the capital stocks between two adjacent years.⁵ In our sample, both net investment and disinvestment over time is observed for nearly every country. China is the notable exception, recording net investment in all years, except in 2006. Regulatory pressure has led some Western countries' mills to shut-down ([ETSAP, 2015, page 5](#)).⁶

With non-negligible industry-level price differences across countries, capital and output are converted to international dollars using the industry purchasing parity power (PPP) exchange rates. The industry PPP exchange rates are obtained from [Inklaar and Timmer \(2014\)](#) and are defined in 2005 prices. Price indices for each period relative to the USA with the industry PPP exchange rates are computed to express the GO and capital at 2005 international dollars.

The emissions associated with the pulp and paper manufacturing industry can be attributed to (i) the combustion of on-site fuels, and (ii) non-energy-related emissions sources, such as CO₂ emissions from the lime kiln chemical reactions ([EPA, 2010](#)). The undesirable outputs, CO₂, N₂O and SO_x, are measured in tons, except CO₂ emissions which are expressed in kilotons. Given the data set does not include information on productive capital and abatement capital, the DEA model cannot distinguish between adjustment costs underlying investment in productive capital and the ones underlying investment in abatement capital.

Summary statistics of the variables by country are presented in Appendix D, Table D. The USA and China are the major pulp and paper producing countries in the world ([ETSAP, 2015](#)). In this sam-

Table 1
Descriptive statistics of environmental efficiency for each country.

Country	Average	Std. Dev.	Minimum	Maximum
Australia	0.099	0.121	0.000	0.296
Austria	0.000	0.000	0.000	0.000
Belgium	0.000	0.000	0.000	0.000
Brazil	0.000	0.000	0.000	0.000
Bulgaria	0.161	0.180	0.000	0.470
Canada	0.019	0.071	0.000	0.265
China	0.756	0.542	0.000	1.693
Cyprus	0.000	0.000	0.000	0.000
Czech Republic	0.013	0.014	0.000	0.041
Denmark	0.375	0.220	0.000	0.675
Estonia	0.000	0.000	0.000	0.000
Finland	0.119	0.112	0.000	0.274
France	0.000	0.000	0.000	0.000
Germany	0.000	0.000	0.000	0.000
Great Britain	0.329	0.355	0.000	0.947
Greece	0.149	0.129	0.000	0.424
Hungary	0.000	0.000	0.000	0.000
India	0.000	0.000	0.000	0.000
Indonesia	0.289	0.103	0.118	0.429
Ireland	0.703	0.167	0.338	0.931
Italy	0.000	0.000	0.000	0.000
Japan	0.000	0.000	0.000	0.000
Latvia	0.062	0.068	0.000	0.176
Lithuania	0.012	0.031	0.000	0.094
Luxembourg	0.001	0.002	0.000	0.007
Malta	0.000	0.000	0.000	0.000
Mexico	0.000	0.000	0.000	0.000
Netherlands	0.063	0.066	0.000	0.149
Poland	0.000	0.000	0.000	0.000
Portugal	0.000	0.000	0.000	0.000
Romania	0.183	0.144	0.019	0.438
Russia	0.000	0.000	0.000	0.000
Slovakia	0.000	0.000	0.000	0.000
Slovenia	0.018	0.029	0.000	0.097
South Korea	0.000	0.000	0.000	0.000
Spain	0.000	0.000	0.000	0.000
Sweden	0.000	0.000	0.000	0.000
Turkey	0.002	0.003	0.000	0.008
USA	5.639	3.598	0.000	10.384

ple, the two nations alone account for 51% of the value of the gross output.

4. Empirical results

The direction vector defined for the DEA model in (2), used to compute environmental efficiency, is $g_y = 1, g'_E = (1, 1, 1)$, implying equal “weights” for the good output and emissions with all countries being evaluated in the same direction ([Färe et al., 2008](#)). Given the choice of the directional vector, the DEA model in (2) is additive and the distance to the production-environmental frontier would be dependent of the measurement units, the magnitude of the variables, and the choice of direction. In order to address these measurement issues, each input factor and output is normalized by its mean.

Table 1 presents the summary statistics of the inefficiency scores for each country, generated by the adjustment-cost DEA model in (2).⁷ USA, China, and Ireland are the most environmentally inefficient countries in the pulp and paper sector (Table 1). The USA environmental inefficiency score is approximately seven times China's inefficiency score and eight times the environmental inefficiency score of Ireland. Besides USA and China, the other significant pulp and paper producers in our sample are Japan, Germany, Great Britain, France, Canada, India, Brazil, South Korea, Sweden, Russia, and Finland. Among this group, most coun-

⁷ Summary statistics of the inefficiency scores for each year are presented in Table E.1 in Appendix E.

³ Taiwan cannot be considered due to lack of information on some variables.

⁴ According to [IEA \(2008\)](#), approximately two-thirds of energy consumption is fuel, while the remaining third is electricity, either from the grid or produced on site. Unlike other industrial sectors, the pulp and paper sector also produces energy from biomass residues.

⁵ The data set does not include information on gross expenditures on capital and gross retirements of capital that would allow to computing a measure of investment/disinvestment. As a result, the time period of the analysis is 1996–2009.

⁶ Foreign direct investment where a parent company builds a subsidiary operation in a foreign country, known as greenfield investment, is not common, particularly in Western countries. Investors in Europe and North America tend to increase cost-efficiency and competitiveness at the existing mills. For example, no greenfield investment has occurred over the final decade for the large pulp producing countries such as USA, Canada, Finland and Sweden. However, greenfield investment has taken place in countries such as Brazil and China ([ETSAP, 2015, page 6](#)).

Table 2
The potential average changes in emissions and gross output for each country if inefficiency is eliminated.

Country	CO ₂ (kilotons)	N ₂ O(tons)	SO _x (tons)	GO(million PPP US\$)
Australia	519.922	26.636	2316.5095	4131.730
Austria	0.000	0.000	0.000	0.000
Belgium	0.000	0.000	0.000	0.000
Brazil	0.000	0.000	0.000	0.000
Bulgaria	846.191	43.351	3770.342	6724.540
Canada	99.840	5.115	444.853	793.412
China	7220.128	369.833	32165.420	57368.174
Cyprus	0.377	0.019	1.679	2.994
Czech Republic	69.700	3.571	310.558	553.891
Denmark	1979.469	101.409	8819.847	15730.514
Estonia	0.000	0.000	0.000	0.000
Finland	628.427	32.195	2800.058	4994.004
France	1.130	0.058	5.036	8.982
Germany	0.000	0.000	0.000	0.000
Great Britain	1735.332	88.902	7732.055	13790.398
Greece	783.650	40.147	3491.679	6227.535
Hungary	0.000	0.000	0.000	0.000
India	0.000	0.000	0.000	0.000
Indonesia	1522.843	78.016	6785.273	12101.777
Ireland	3850.434	197.260	17156.230	30598.754
Italy	0.000	0.000	0.000	0.000
Japan	0.000	0.000	0.000	0.000
Latvia	328.530	16.831	1463.819	2610.774
Lithuania	62.918	3.223	380.342	499.999
Luxembourg	6.405	0.328	28.538	50.900
Malta	0.000	0.000	0.000	0.000
Mexico	1.130	0.058	5.036	8.982
Netherlands	330.791	16.947	1473.891	2628.739
Poland	0.000	0.000	0.000	0.000
Portugal	0.000	0.000	0.000	0.000
Romania	964.115	49.392	4295.773	7661.665
Russia	0.000	0.000	0.000	0.000
Slovakia	0.000	0.000	0.000	0.000
Slovenia	94.942	4.864	423.030	754.490
South Korea	0.000	0.000	0.000	0.000
Spain	0.000	0.000	0.000	0.000
Sweden	0.000	0.000	0.000	0.000
Turkey	8.665	0.444	38.610	68.862
USA	29740.266	1523.609	132512.600	236340.947
TOTAL	50795.205	2602.206	226321.200	403652.062

tries (i.e., Brazil, France, Germany, India, Japan, Russia, South Korea and Sweden) are environmentally efficient in each year, and the remaining countries – Canada, Finland and Great Britain – are, on average, environmentally inefficient.

Table 2 presents the potential gains to GO and reductions in emissions on average for each country, if inefficiency was eliminated. The USA could expand GO by 236,341 million PPP US\$ per year and decrease CO₂ by 29,740.3 kilotons, N₂O by 1,523.6 tons and SO_x by 132,512.6 tons per year.⁸ The annual average decrease in CO₂, N₂O and SO_x in the USA represent approximately 58.6% of the sum of the annual reduction of each emission that could be achieved if all countries in the sample were fully efficient. As the second most environmentally inefficient country, Table 2 indicates that China could increase GO by 57,368.2 million PPP US\$ per year and simultaneously, decrease CO₂, N₂O and SO_x by, respectively 7,220.1 kilotons, 369.8 tons and 32,165.4 tons per year. The annual average decrease of CO₂, N₂O and SO_x in China represent approximately 14.21% of the sum of the annual reductions for these activities across all countries. Taken together, the annual re-

⁸ The pulp and paper manufacturing process is highly energy intensive. Natural gas, fuel oil, purchased electricity, coal and biomass-based materials are the primary energy-related emissions sources from USA pulp and paper mills. The first four energy sources contributed to an estimated 80% or more of the industry's energy related emissions in 2002. Therefore, a main option to reduce emissions is to improve energy efficiency that can lead to reduced fuel consumption or reduced electricity demand (EPA, 2010).

duction of each type of emission in the USA and China combined represent 72.8% of the total sum of emission reduction in the sample, indicating the contribution of these two countries is crucial for a reduction in emissions at the global level.

Given that $\beta'_{b^+}(0) \leq \beta'_{b^-}(0)$ (Podinovski, 2019), Table 3 presents the lower and upper bounds on the shadow price of pollutants for each country.⁹ The upper bound on shadow prices (i.e., left-hand side shadow prices) of CO₂ and SO_x are on average positive for the majority of the countries with a defined price, meaning that an increase in CO₂ (SO_x) emissions generates an increase in GO, holding the inputs and SO_x and N₂O (CO₂ and N₂O) emissions constant. In contrast, the lower bound on shadow prices (i.e., right-hand side shadow prices) of CO₂ and SO_x are on average negative for the majority of the countries with a defined price.¹⁰ A negative shadow price implies that a reduction in CO₂

⁹ Summary statistics of the left- and right-hand side of the shadow prices of emissions are presented in Tables E.2-E.7 in Appendix E. Several +∞ (-∞) are reported in Tables E.2, E.4 and E.6 (Tables E.3, E.5 and E.7), indicating that the optimal value of the maximization problem in (6) (minimization problem in (7)) is unbounded for some countries.

¹⁰ Analyzing the right- and left-hand shadow prices of CO₂ and SO_x for all countries in all years - which are not reported in the paper due to lack of space -, one can verify that they coincide in several cases. For example, for China, right- and left-hand shadow prices of CO₂ (SO_x) are equal in 1997-2004 and 2008-2009 (in 1996, 2001 and 2003). For USA right- and left-hand shadow prices of CO₂ (SO_x) are equal in 1996 and 2005, 2007 and 2008 (in 1996 and 2005). The equality between the right- and left-hand shadow prices indicates that the projection of the observa-

Table 3
Lower and upper bounds on the shadow price of bad outputs for each country, US\$/ton (PPP 2005).

Country	CO ₂		SO _x		N ₂ O	
	Lower bound	Upper bound	Lower bound	Upper bound	Lower bound	Upper bound
Australia	-5.434	10.520	-1.043	-0.385	6.688	1.044 ^(a)
Austria	-∞	3.270	-∞	+∞	-∞	+∞
Belgium	-∞	-0.570	-0.779	+∞	13.922	+∞
Brazil	4.842	7.328	-0.300	-0.007	-19.464	-11.150
Bulgaria	-∞	+∞	-∞	+∞	-∞	+∞
Canada	-∞	+∞	-∞	+∞	-∞	+∞
China	-0.121	2.069	-0.634	-0.176	-2.731	9.395
Cyprus	-∞	-4.292	-∞	+∞	-∞	+∞
Czech Republic	-3.517	8.557	-0.659	0.638	3.844	+∞
Denmark	9.405	+∞	0.000	+∞	-∞	+∞
Estonia	3.851	4.078	-1.291	-1.141	-22.723	0.524
Finland	-∞	1.663	-∞	+∞	-∞	+∞
France	-5.495	5.173	-0.461	1.120	-12.391	3.945
Germany	-8.295	8.469	-0.325	4.414	-1.058	11.719
Great Britain	-7.513	6.320	-0.666	5.518	-23.640	29.101
Greece	-∞	+∞	-∞	+∞	-∞	-8.257
Hungary	1.018	+∞	-2.243	0.358	-∞	+∞
Indonesia	-3.938	7.415	-1.641	6.936	3.318	+∞
India	-2.467	6.316	-0.439	0.762	-10.455	-27.312 ^(b)
Ireland	-16.09	+∞	-3.975	+∞	+∞	+∞
Italy	-∞	+∞	-0.469	+∞	-∞	+∞
Japan	3.755	7.794	2.536	7.408	-∞	12.065
Latvia	-8.363	10.327	0.097	9.906	-14.786	-14.786
Lithuania	0.149	14.342	0.807	6.426	-∞	+∞
Luxembourg	-∞	17.126	-∞	4.518	22.076	+∞
Malta	4.386	+∞	-∞	+∞	-∞	+∞
Mexico	1.145	9.071	-1.171	-0.604	0.760	-4.564 ^(c)
Netherlands	-∞	10.445	-∞	+∞	-∞	+∞
Poland	-0.867	4.890	-0.472	0.044	-15.555	-11.362
Portugal	-∞	+∞	-∞	+∞	-∞	+∞
Romania	-∞	+∞	-∞	+∞	-18.342	+∞
Russia	2.348	6.989	3.414	10.197	-24.169	-3.865
Slovakia	-∞	-1.223	-∞	-0.534	-∞	+∞
Slovenia	-∞	-6.035	-∞	+∞	-∞	+∞
South Korea	-∞	2.894	-∞	+∞	-10.259	+∞
Spain	-10.215	3.087	-1.073	0.793	-12.432	-26.747
Sweden	-∞	+∞	-∞	+∞	-∞	5.282
Turkey	-2.382	2.670	-1.167	0.995	-12.887	+∞
USA	-6.897	0.656	-1.085	-0.041	-0.974	10.638

Table 4
Wilcoxon signed ranks tests on the right- and left-hand shadow prices of CO₂ (n = 133) ^a.

Two-tailed test	Lower tailed-test	Upper-tailed test
H ₀ : E($\hat{\beta}'_{CO_2+}$) = 0	H ₀ : E($\hat{\beta}'_{CO_2+}$) ≥ 0	H ₀ : E($\hat{\beta}'_{CO_2+}$) ≤ 0
H ₁ : E($\hat{\beta}'_{CO_2+}$) ≠ 0	H ₁ : E($\hat{\beta}'_{CO_2+}$) < 0	H ₁ : E($\hat{\beta}'_{CO_2+}$) > 0
p-value=0.00031	p-value=0.000155	p-value=0.999845
H ₀ : E($\hat{\beta}'_{CO_2-}$) = 0	H ₀ : E($\hat{\beta}'_{CO_2-}$) ≥ 0	H ₀ : E($\hat{\beta}'_{CO_2-}$) ≤ 0
H ₁ : E($\hat{\beta}'_{CO_2-}$) ≠ 0	H ₁ : E($\hat{\beta}'_{CO_2-}$) < 0	H ₁ : E($\hat{\beta}'_{CO_2-}$) > 0
p-value=0.00006	p-value=0.99997	p-value=0.00003

^a Precluding the values of infinity and the ties results in 133 observations.

(SO_x) emissions implies an increase in GO, while keeping constant the inputs and SO_x and N₂O (CO₂ and N₂O) emissions. For N₂O, the upper and lower bounds on the shadow price are, on average, negative for the majority of the countries with a defined price.¹¹

Excluding the cases of +∞ and -∞, the signs of the average (left- and right-hand side) shadow prices of bad outputs are corroborated by the Wilcoxon signed ranks tests on the right- and left-hand shadow prices (Tables 4–6). In this study, shadow prices of bad outputs are found to be positive or negative across coun-

tries. A positive shadow price of a bad output means that reducing its emission level implies an economic cost for the industry (i.e., a decrease in the GO, holding the inputs and other emissions constant). A negative price of a bad output means that a reduction in its emission level is accompanied by an increase in GO, while keeping the inputs and other emissions constant, implying an economic benefit for the industry.

It may seem paradoxical negative shadow prices of bad outputs. Yet, there may be technical possibilities of decreasing the bad output and increasing the good output. Murty (2010) and Murty et al (2012) consider the case of a production technology with an output as a source of emission, where a reduction in the emission level has a positive effect on intended production. Ray et al (2018) acknowledge the possibility of a detrimental effect of the bad output on the productivity of the neutral input (e.g., labor). In

tions occur at the relative interiors of some facets of the production frontier where the one sided derivatives are equal to each other.

¹¹ Considering the right- and left-hand shadow prices of N₂O for all countries in all years, one concludes that they are equal in several cases. For example, for China, right- and left-hand shadow prices are equal in 1999, 2001 and 2003. For USA right- and left-hand shadow prices are equal in 1996 and 2005.

Table 5
Wilcoxon signed ranks tests on the right- and left-hand shadow prices of N₂O (n = 126) ^a.

Two-tailed test	Lower tailed-test	Upper-tailed test
H ₀ : E($\tilde{\beta}'_{N_2O+}$) = 0	H ₀ : E($\tilde{\beta}'_{N_2O+}$) ≥ 0	H ₀ : E($\tilde{\beta}'_{N_2O+}$) ≤ 0
H ₁ : E($\tilde{\beta}'_{N_2O+}$) ≠ 0	H ₁ : E($\tilde{\beta}'_{N_2O+}$) < 0	H ₁ : E($\tilde{\beta}'_{N_2O+}$) > 0
p-value=0.01157	p-value=0.005785	p-value=0.99438
H ₀ : E($\tilde{\beta}'_{N_2O-}$) = 0	H ₀ : E($\tilde{\beta}'_{N_2O-}$) ≥ 0	H ₀ : E($\tilde{\beta}'_{N_2O-}$) ≤ 0
H ₁ : E($\tilde{\beta}'_{N_2O-}$) ≠ 0	H ₁ : E($\tilde{\beta}'_{N_2O-}$) < 0	H ₁ : E($\tilde{\beta}'_{N_2O-}$) > 0
p-value=0.04497	p-value=0.022485	p-value=0.978565

^a Precluding the values of infinity and the ties results in 126 observations.

Table 6
Wilcoxon signed ranks tests on the right- and left-hand shadow prices of SO_x (n = 146) ^a.

Two-tailed test	Lower tailed-test	Upper-tailed test
H ₀ : E($\tilde{\beta}'_{SO_x+}$) = 0	H ₀ : E($\tilde{\beta}'_{SO_x+}$) ≥ 0	H ₀ : E($\tilde{\beta}'_{SO_x+}$) ≤ 0
H ₁ : E($\tilde{\beta}'_{SO_x+}$) ≠ 0	H ₁ : E($\tilde{\beta}'_{SO_x+}$) < 0	H ₁ : E($\tilde{\beta}'_{SO_x+}$) > 0
p-value=0.00001	p-value=0.00005	p-value=0.99995
H ₀ : E($\tilde{\beta}'_{SO_x-}$) = 0	H ₀ : E($\tilde{\beta}'_{SO_x-}$) ≥ 0	H ₀ : E($\tilde{\beta}'_{SO_x-}$) ≤ 0
H ₁ : E($\tilde{\beta}'_{SO_x-}$) ≠ 0	H ₁ : E($\tilde{\beta}'_{SO_x-}$) < 0	H ₁ : E($\tilde{\beta}'_{SO_x-}$) > 0
p-value=0.00006	p-value=0.99997	p-value=0.00003

^a Precluding the values of infinity and the ties results in 146 observations.

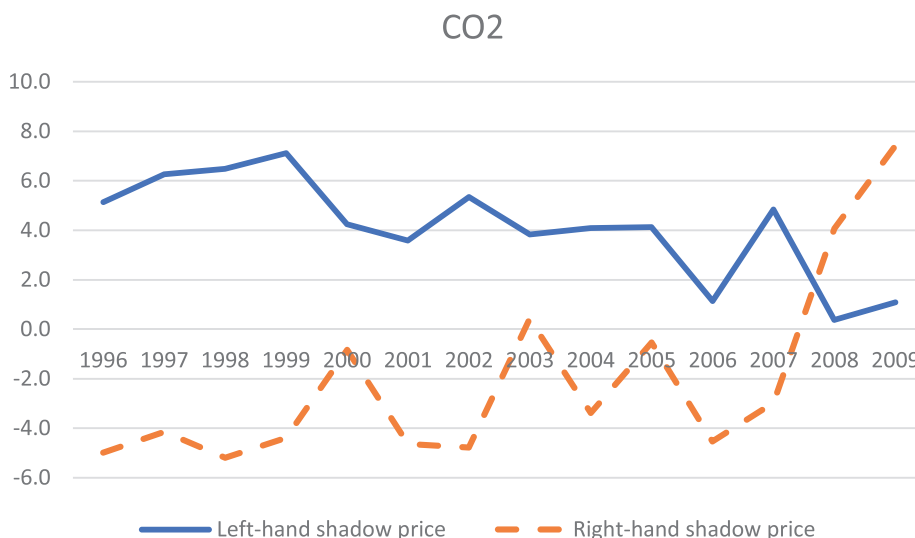


Fig. 1. Time trend of the shadow prices of CO₂.

that case, pollution reduction may cause the productivity of the resources used in the production of the good output to improve significantly so that the good output increases even as the bad output is reduced. Furthermore, according to Moya and Pavel (2018), there is scope to reduce GHG emissions in the pulp and paper industry and increase production through energy efficiency improvements and by switching sources of energy.

Figs. 1, 2 and 3 show the time trend of the shadow prices of bad outputs. The time trend of the left-hand shadow prices of CO₂ and SO_x are similar (Figs. 1 and 2). The left-hand shadow price of CO₂ (SO_x) shows a declining trend over time, indicating that the loss in GO due to a decrease in CO₂ (SO_x) emissions is decreasing over time, holding inputs and SO_x (CO₂) and N₂O emissions constant. In contrast, the right-hand side of the CO₂ shadow price fluctuates over time until 2006, showing an increasing trend after 2006 and becoming positive in the last two years (Fig. 1); the right-hand side shadow price of SO_x fluctuates over time during the sample period (Fig. 2). Similarly, the left- and the right-hand side of shadow prices of N₂O fluctuate over time (Fig. 3).

Tables 7 and 8 report the Spearman rank correlation coefficient tests (Conover, 1999) on the right- and left-hand shadow prices

of each pollutant, in absolute value, and the ratio of its emission level and GO. The purpose of these statistical tests is to investigate how the shadow prices of each pollutant changes with its emission level per one million of US\$ (PPP 2005) of GO. Results for CO₂ and SO_x are similar: larger (smaller) values of the right- and left-hand shadow prices of CO₂ (SO_x), in absolute value, tend to be associated with smaller (larger) values of the ratio of CO₂ (SO_x) emissions to GO. These results indicate that the marginal cost (or benefit) of reducing any of these emissions increases as the ratio of the emission level per one million of US\$ (PPP 2005) of GO decreases. Results on N₂O are quite different for the right- and left-hand shadow prices. The right-hand shadow price of N₂O, in absolute value, and the ratio N₂O/GO are mutually independent. In contrast, there is a tendency for smaller values of the left-hand shadow price of N₂O, in absolute value, to be paired with larger values of the ratio of N₂O emissions to GO. Thus, the marginal benefit of reducing the N₂O emissions increases as the ratio of the emission level per one million of US\$ (PPP 2005) of GO decreases.

OECD (2016) estimates the price of CO₂ emissions (or a CO₂ tax) based on taxes on energy and emissions trading systems and the share of emissions priced by these instruments. The data are com-

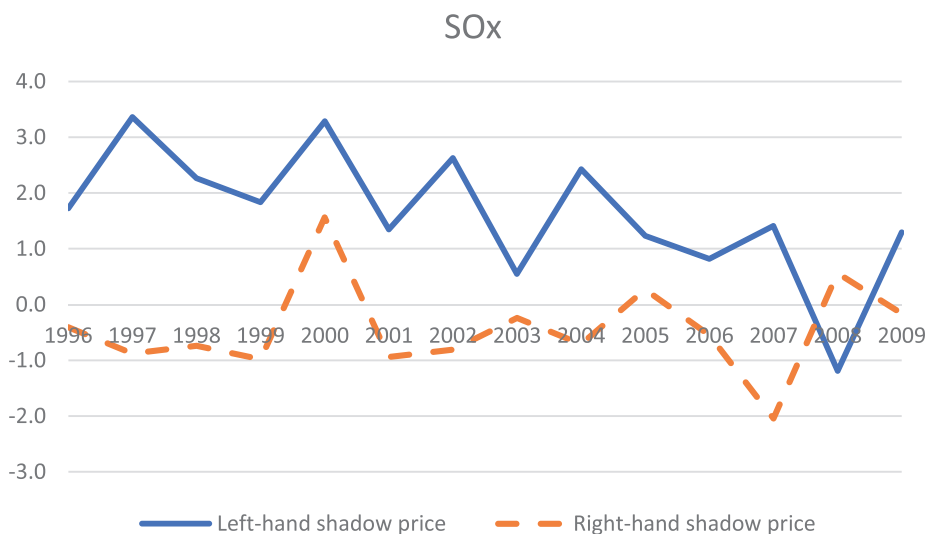


Fig. 2. Time trend of the shadow prices of SO_x.



Fig. 3. Time trend of the shadow prices of N₂O.

Table 7
The Spearman rank correlation coefficient tests on the right-hand shadow price of each bad output and the ratio of the emission level and GO

Two-tailed test	Lower-tailed test	Upper-tailed test
CO ₂ H ₀ : $ \tilde{\beta}'_{CO_2+} $ and CO ₂ /GO are mutually independent H ₁ : (a), or (b)* p-value = 0.0759	H ₀ : $ \tilde{\beta}'_{CO_2+} $ and CO ₂ /GO are mutually independent H ₁ : (a) p-value = 0.03795	H ₀ : $ \tilde{\beta}'_{CO_2+} $ and CO ₂ /GO are mutually independent H ₁ : (b) p-value = 0.96205
N ₂ O H ₀ : $ \tilde{\beta}'_{N_2O+} $ and N ₂ O/GO are mutually independent H ₁ : (a), or (b)* p-value = 0.99601	H ₀ : $ \tilde{\beta}'_{N_2O+} $ and N ₂ O/GO are mutually independent H ₁ : (a) p-value = 0.498005	H ₀ : $ \tilde{\beta}'_{N_2O+} $ and N ₂ O/GO are mutually independent H ₁ : (b) p-value = 0.501995
SO _x H ₀ : $ \tilde{\beta}'_{SO_x+} $ and SO _x /GO are mutually independent H ₁ : (a), or (b)* p-value = 0.00145	H ₀ : $ \tilde{\beta}'_{SO_x+} $ and SO _x /GO are mutually independent H ₁ : (a) p-value = 0.000725	H ₀ : $ \tilde{\beta}'_{SO_x+} $ and SO _x /GO are mutually independent H ₁ : (b) p-value = 0.999725

(a) There is a tendency for the smaller (larger) values of the shadow price of the bad output to be paired with the larger (smaller) values of Emission level/GO. (b) There is a tendency for larger values of the shadow price of the bad output and Emission level/GO to be paired together.

Table 8
The Spearman rank correlation coefficient tests on the left-hand shadow price of each bad output and the ratio of the emission level and GO.

Two-tailed test	Lower-tailed test	Upper-tailed test
CO ₂ H ₀ : $ \tilde{\beta}'_{CO_2} $ and CO ₂ /GO are mutually independent H ₁ : (a), or (b)* p-value = 0.00069	H ₀ : $ \tilde{\beta}'_{CO_2} $ and CO ₂ /GO are mutually independent H ₁ : (a) p-value = 0.000345	H ₀ : $ \tilde{\beta}'_{CO_2} $ and CO ₂ /GO are mutually independent H ₁ : (b) p-value = 0.999655
N ₂ O H ₀ : $ \tilde{\beta}'_{N_2O} $ and N ₂ O/GO are mutually independent H ₁ : (a), or (b)* p-value = 0.04942	H ₀ : $ \tilde{\beta}'_{N_2O} $ and N ₂ O/GO are mutually independent H ₁ : (a) p-value = 0.02471	H ₀ : $ \tilde{\beta}'_{N_2O} $ and N ₂ O/GO are mutually independent H ₁ : (b) p-value = 0.247978
SO _x H ₀ : $ \tilde{\beta}'_{SO_x} $ and SO _x /GO are mutually independent H ₁ : (a), or (b)* p-value = 0.00006	H ₀ : $ \tilde{\beta}'_{SO_x} $ and SO _x /GO are mutually independent H ₁ : (a) p-value = 0.00003	H ₀ : $ \tilde{\beta}'_{SO_x} $ and SO _x /GO are mutually independent H ₁ : (b) p-value = 0.99997

(a) There is a tendency for the smaller (larger) values of the shadow price of the bad output to be paired with the larger (smaller) values of Emission level/GO. (b) There is a tendency for larger values of the shadow price of the bad output and Emission level/GO to be paired together.

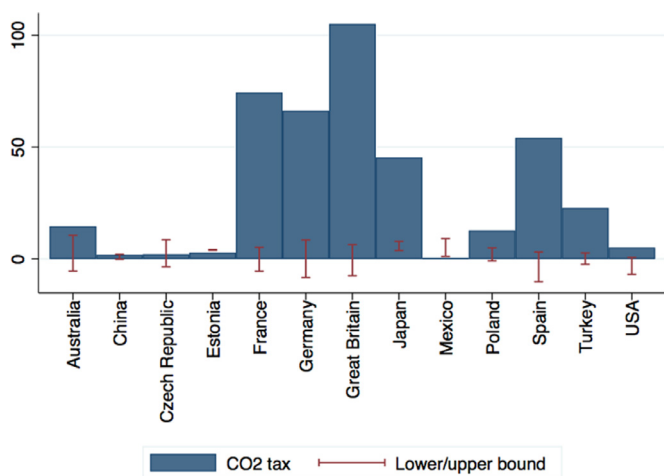


Fig. 4. Upper and lower bounds on the shadow price of CO₂ and the CO₂ tax.

puted by sector and country in the year of 2016.¹² Given that some countries do not have an emission trading system, the price of CO₂ emissions are computed from taxes on energy for 20 countries and converted into US\$/ton (PPP 2005).¹³ Though the prices of CO₂ (or CO₂ taxes) are outside our sample period and not available for all countries in our sample, we attempt to illustrate the expected behavior of the pulp and paper sector in some countries by comparing these prices with the shadow prices of CO₂ in Table 3.¹⁴ Fig. 4 presents the OECD CO₂ tax and defined upper and lower bounds on the shadow prices of CO₂.¹⁵ Analyzing the CO₂ taxes in Fig. 4, one verifies that France, Germany, Great Britain, Japan and Spain are the countries with the highest price of CO₂ emissions (or CO₂ tax). In contrast, China, Czech Republic, Estonia, Mexico and USA are the countries with the lowest price of CO₂ emissions.

Focusing on cases with defined and positive upper bounds on the shadow price of CO₂ and comparing with the CO₂ tax, we verify in Fig. 4 that the upper bound is lower than the CO₂ tax for the

majority of the countries (e.g., Australia, France, Germany, Great Britain, Japan, Turkey, USA).¹⁶ Thus, the marginal cost of reducing emissions is less than the CO₂ tax. The reaction of the pulp and paper sector to the difference between the marginal cost of abatement and the CO₂ tax depends on the marginal cost function. If the marginal cost of CO₂ abatement is increasing and strictly convex (Ambec & Coria, 2013), the pulp and paper sector for those countries has incentives to decrease CO₂ emissions (i.e., to increase the abatement of CO₂).¹⁷

There are, however, four countries where the upper bound on the shadow price of CO₂ is greater than the CO₂ tax: China, Czech Republic, Estonia and Mexico (Fig. 4).¹⁸ Thus, the marginal cost of reducing CO₂ emissions would be greater than the CO₂ tax. If the marginal cost of CO₂ abatement is increasing and strictly convex, the pulp and paper sector for those countries has incentives to increase (i.e., reduce abatement) CO₂ emissions.

Table 9 presents lower and upper bounds on the marginal rate of transformation between pollutants, based on, respectively, the right- and left-hand marginal rates of transformation between bad outputs.¹⁹ Results are, in general, inconclusive with respect to whether pollutants are substitutes or complements since the lower bound is negative and the upper bound is positive. This issue needs further investigation probably at a more disaggregated level (e.g., plant level), given its importance for policy design and implementation.

There are however a few exceptions in Table 9 that allow inferences on the choice of policy instruments to regulate emissions. Results in Table 9 indicate that N₂O and CO₂ are complements in Denmark and substitutes in Romania and Turkey. SO_x and CO₂ are complements (substitutes) in Bulgaria, Hungary, Indonesia, Slovakia, Slovenia and Turkey (Denmark, Latvia, Lithuania and The Netherlands). N₂O and SO_x are complements (substitutes) in Bulgaria, Hungary and Indonesia (Denmark). Following Ambec and Coria (2013), a mixed policy instrument (i.e., taxes are used to control the emissions of one pollutant and an emission norm or non-

¹² Unfortunately, similar information was not found for N₂O and SO_x emissions.

¹³ Table E.14 in Appendix E report the OECD price of CO₂.

¹⁴ The CO₂ tax was not used as an environmental policy instrument in many countries over 1996–2009 (FCCC, 2014).

¹⁵ Countries with a range for the shadow prices of CO₂ equal to $[-\infty, +\infty]$ (e.g., Canada, Greece, Italy, Portugal, Sweden) are not represented in Figure 4. Also, cases of undefined upper or lower bounds on the shadow price of CO₂ are not represented in Figure 4 (e.g., the upper bound of the CO₂ shadow price of Denmark is $+\infty$; the lower bound for The Netherlands is $-\infty$).

¹⁶ As mentioned before, the upper bound (lower bound) on shadow price CO₂ is on average positive (negative) for the majority of the countries with a defined price.

¹⁷ Ambec and Coria (2013) assume that the marginal cost of abatement is increasing and strictly convex. The assumption of an increasing marginal cost abatement is consistent with results on Tables 7 and 8. From those tables, the shadow price of CO₂ is decreasing with the level of emissions per one million of US\$ (PPP 2005) of GO implying it is likely increasing with the abatement level.

¹⁸ In the case of Estonia and Mexico, both lower and upper bounds are positive and greater than the CO₂ tax.

¹⁹ Tables E.15–E.20, in Appendix E, presents the summary statistics of left- and right-hand marginal rates of transformation between two bad outputs.

Table 9
Lower and upper bounds on the marginal rate of transformation (MRT) between bad outputs for each country.

Country	MRT of N ₂ O for CO ₂ (kilotons/tons)		MRT of SO _x for CO ₂ (kilotons/tons)		MRT of N ₂ O for SO _x (tons/tons)	
	Lower bound	Upper bound	Lower bound	Upper bound	Lower bound	Upper bound
Australia	-6.573	+∞	-∞	0.088	-∞	0.084
Austria	-9.808	3.294	-0.022	0.310	-0.011	0.103
Belgium	-2.579	3.160	-0.019	0.074	-0.299	0.022
Brazil	-4.697	2.418	-0.038	0.087	-0.021	0.259
Bulgaria	-6.527	4.969	0.058	0.372	0.001	0.236
Canada	-3.627	3.538	-0.006	0.091	-0.004	0.082
China	-16.737	1.837	-0.100	0.111	-0.078	0.043
Cyprus	-7.685	2.096	-0.016	0.111	-0.084	0.029
Czech Republic	-30.118	1.867	-0.172	0.166	-0.027	0.035
Denmark	3.543	46.675	-19.743	-1.320	-0.111	-0.120
Estonia	-15.595	3.918	-0.020	3.319	-0.054	0.143
Finland	-4.728	6.624	-0.156	0.089	-0.326	0.103
France	-1.505	1.026	-0.069	0.022	-0.060	0.018
Germany	-5.423	0.742	-0.079	0.047	-0.082	0.034
Great Britain	-7.402	9.330	-1.565	1.097	-0.148	0.041
Greece	-3.416	8.533	-0.254	0.142	-0.016	0.070
Hungary	-26.125	4.762	0.009	0.273	0.002	0.008
Indonesia	-4.097	2.707	0.018	0.221	-0.005	0.008
India	-23.738	8.251	-0.138	0.162	-0.018	0.006
Ireland	-∞	+∞	-∞	0.522	-∞	+∞
Italy	-8.367	+∞	-∞	-0.451	-∞	0.005
Japan	-1.321	5.405	-0.349	0.008	-0.132	0.005
Latvia	-9.700	11.279	-0.668	-0.046	-0.025	0.129
Lithuania	-1.014	13.774	-0.544	-0.416	-0.009	0.046
Luxembourg	-∞	5.645	-∞	0.515	-0.340	0.220
Malta	-∞	+∞	-∞	0.305	-∞	+∞
Mexico	-26.495	5.685	-0.280	0.695	-0.014	0.007
Netherlands	-∞	9.475	-∞	-1.032	-∞	0.037
Poland	-5.113	4.437	-0.001	0.175	-0.002	0.041
Portugal	-10.930	8.635	-0.018	0.195	-0.043	0.217
Romania	-∞	-10.338	-0.163	0.520	-0.028	0.156
Russia	-11.306	13.358	-1.198	0.094	-0.235	0.134
Slovakia	-1.970	2.598	0.089	0.207	-0.048	0.095
Slovenia	-0.402	3.530	0.039	0.070	-0.066	0.015
South Korea	-10.980	4.662	-0.186	0.310	-0.025	0.016
Spain	-25.122	7.378	-0.385	0.314	-0.018	0.054
Sweden	-1.096	+∞	-∞	0.068	-0.042	0.061
Turkey	-∞	-18.002	0.008	0.290	-0.025	0.069
USA	-3.045	1.397	-0.063	0.059	-0.081	0.036

tradable quota aims to reduce the emissions of the other pollutant) can be a good option in Denmark (Bulgaria, Hungary, Indonesia, Slovakia, Slovenia and Turkey) to control N₂O and CO₂ (SO_x and CO₂) emissions. Moreover, the regulator can improve welfare by using a mixed policy with a tax on one pollutant and a quota on the other pollutant, with a penalty for exceeding the quota that must be proportional to the deviation from the quota itself (Ambec & Coria, 2013).

In the case of SO_x and CO₂ (N₂O and CO₂), which are substitutes in Denmark, Latvia, Lithuania and The Netherlands (Romania and Turkey), Ambec and Coria (2013) suggest either a tax or a quota in these cases. Furthermore, Ambec and Coria (2013) argue that in the case of a tax, the tax rate should reflect the social benefit from reducing pollution and the damage of uncontrolled pollution.

Achieving environmental and economic aims simultaneously is an important challenge. Besides policy measures, other factors (e.g., technological factors, corporate responsibility) have probably an important role in explaining the environmental performance of the pulp and paper sector of these countries. A reasonable range of production technologies have the potential to reduce emissions but available mitigation options are often not fully used due to the presence of barriers like limited access to capital, lack of management attention and/or insufficient availability of knowledge (e.g., Fleiter et al., 2012). More recently, companies report their corporate responsibility activities and the concept of sustainability has undergone a major change in industries where companies are integrating sustainability into their business concepts (e.g.,

Schönsleben et al., 2019). Differences in social corporate responsibility across companies and countries are probably another factor to be taken into account when explaining differences in environmental performance.

Using the average shadow prices of net investment (disinvestment) and the fact that $\hat{\beta}_{j^+}'(0) \leq \hat{\beta}_{j^-}'(0)$ ($\hat{\beta}_{j^+}'(0) \leq \hat{\beta}_{j^-}'(0)$), upper and lower bounds on the shadow price of net investment (disinvestment) are presented in Table 10.²⁰ The range of the shadow prices of net investment and disinvestment for some countries (e.g., Austria, Finland, Italy, Greece, Netherlands, Sweden) is $(-\infty, 0]$, which is not informative on the marginal cost of adjustment of these activities. Nevertheless, the ranges of the shadow price of investment and disinvestment for the majority of the countries (e.g., China, Japan, USA, Denmark, France, Germany) are narrower, providing some information on the marginal cost of adjustment underlying investment and disinvestment activities. For China, the ranges of the shadow price of investment and disinvestment are disjoint and, respectively, $[-11.376, -6.089]$ and $[-3.094, 0]$. In this case, the marginal cost of investment is higher than the marginal cost of disinvestment, which is an indication of asymmetric adjustment costs. For the other countries (e.g., USA), the ranges for the shadow prices of investment and disinvestment are different

²⁰ The summary statistics of the left- and right-hand side shadow prices of net investment (disinvestment) for each country, generated by the dual model (C.3) ((C.4)) in Appendix C, are presented, respectively, in Tables E.21 and E.22 (Tables E.23 and E.24) in Appendix E.

Table 10
Upper and lower bounds on the shadow price of net investment and disinvestment (millions US\$ PPP 2005).

Country	Net investment		Net disinvestment	
	Lower bound	Upper bound	Lower bound	Upper bound
Australia	-26.376	-9.033	-24.362	-2.109
Austria	-∞	0.000	-∞	0.000
Belgium	-∞	0.000	0.000	0.000
Brazil	-9.699	0.000	-11.194	-1.778
Bulgaria	-∞	-1.452	-∞	0.000
Canada	-∞	0.000	-∞	0.000
China	-11.376	-6.089	-3.094	0.000
Cyprus	-∞	0.000	-∞	-1.055
Czech Republic	-30.476	-6.612	-31.096	-2.847
Denmark	-16.370	0.000	-29.022	-0.005
Estonia	-5.909	-5.616	-7.954	-1.416
Finland	-∞	0.000	-∞	0.000
France	-28.382	-1.585	-31.985	-0.005
Germany	-28.741	-9.076	-31.216	-2.392
Great Britain	-29.138	-5.477	-20.031	-0.298
Greece	-∞	0.000	-∞	0.000
Hungary	-∞	0.000	-54.481	0.000
India	-18.962	-3.633	-22.961	-1.396
Indonesia	-29.474	-2.349	-26.553	-0.315
Ireland	-31.625	0.000	-24.035	0.000
Italy	-∞	0.000	-∞	0.000
Japan	-12.822	-1.329	-20.387	-2.520
Latvia	-26.159	-3.481	-37.511	-1.853
Lithuania	-21.223	-2.187	-28.265	-0.313
Luxembourg	-16.490	0.000	-35.68	0.000
Malta	-∞	0.000	-54.792	0.000
Mexico	-14.039	-3.215	-18.446	-2.226
Netherlands	-∞	0.000	-∞	0.000
Poland	-18.973	-8.036	-20.373	-1.384
Portugal	-∞	0.000	-∞	0.000
Romania	-∞	0.000	-∞	0.000
Russia	-16.218	-3.018	-16.053	-2.157
Slovakia	-∞	0.000	-∞	0.000
Slovenia	-∞	-2.628	-∞	0.000
South Korea	-∞	0.000	-∞	-0.068
Spain	-17.569	-6.164	-22.326	-5.732
Sweden	-∞	0.000	-∞	0.000
Turkey	-6.389	-0.514	-6.574	-1.537
USA	-22.441	-8.493	-21.608	-2.024

Table 11
Wilcoxon signed ranks test on the right- and left-hand shadow prices of net investment and disinvestment ($n = 261$)^a.

Two-tailed test	Lower-tailed test	Upper-tailed test
$H_0: E(\hat{\beta}_+^{+'}) = E(\hat{\beta}_+^{+'})$	$H_0: E(\hat{\beta}_+^{+'}) \geq E(\hat{\beta}_+^{+'})$	$H_0: E(\hat{\beta}_+^{+'}) \leq E(\hat{\beta}_+^{+'})$
$H_1: E(\hat{\beta}_+^{+'}) \neq E(\hat{\beta}_+^{+'})$	$H_1: E(\hat{\beta}_+^{+'}) < E(\hat{\beta}_+^{+'})$	$H_1: E(\hat{\beta}_+^{+'}) > E(\hat{\beta}_+^{+'})$
$p\text{-value} = 0.0389$	$p\text{-value} = 0.9805$	$p\text{-value} = 0.0195$
$H_0: E(\hat{\beta}_-^{+'}) = E(\hat{\beta}_-^{+'})$	$H_0: E(\hat{\beta}_-^{+'}) \geq E(\hat{\beta}_-^{+'})$	$H_0: E(\hat{\beta}_-^{+'}) \leq E(\hat{\beta}_-^{+'})$
$H_1: E(\hat{\beta}_-^{+'}) \neq E(\hat{\beta}_-^{+'})$	$H_1: E(\hat{\beta}_-^{+'}) < E(\hat{\beta}_-^{+'})$	$H_1: E(\hat{\beta}_-^{+'}) > E(\hat{\beta}_-^{+'})$
$p\text{-value} = 0.0389$	$p\text{-value} = 0.9805$	$p\text{-value} = 0.0195$

^a Precluding the values of infinity and the ties results in 261 observations.

but not disjoint, requiring further investigation whether adjustment costs are symmetric or asymmetric.

Table 11 reports the Wilcoxon signed ranks tests (Conover, 1999) on the right-hand shadow prices of investment and disinvestment and also on the left-hand shadow prices of investment and disinvestment to assess whether adjustment costs are symmetric or asymmetric. Results indicate that adjustment costs are asymmetric since the average shadow price of investment is statistically significantly different from the average shadow price of disinvestment at the 4% significance level. Moreover, the average shadow price of disinvestment tends to be greater (or, in absolute value, less) than the average shadow price of investment at the 2% significance level. This indicates that marginal cost of investment is greater than the marginal cost of disinvestment and thus, the

speed of adjustment in this industry to expand the scale of the operation is lower than the speed of adjustment to scale it back.²¹ This result is consistent with irreversibility and the “real option” effect. In the presence of irreversibility and substantial demand shocks, disinvestments are delayed because firms try to avoid the investment costs they have to bear in favorable times and keep

²¹ Explorations of non-convex adjustment aim to investigate the prospect of asymmetry in adjustment as a motivation for lumpy investment, where expansions can occur at a different rate than contractions. Oude Lansink and Stefanou (1997) take a dynamic dual modeling perspective and find the presence of adjustment asymmetry at the farm-level, and Palm and Pfann (1998) explore the asymmetry of adjustment at a macro level focusing on in U.K. manufacturing.

the option value of maintaining capital investments (Kühn & Van Reenen, 2009, p. 400).

The pulp and paper sector is characterized by considerable irreversibility of investments due to the combination of large sunk costs and substantial demand shocks. With highly industry-specific investments in the pulp and paper sector, disinvestments can occur only by scrapping a plant, which in turn also involves hazardous materials removal costs and no recovery of benefits (Kühn & Van Reenen, 2009, p. 400). As a result, we expect lumpiness of investments and periods of inactivity (zero investment) at the plant level.²²

5. Concluding remarks

Promoting sustainable development at the national and global levels necessarily entails assessing the ability to produce goods and services while minimizing the damage to the environment. The construction of effective policy to promote environmental efficiency can use the shadow prices of bad outputs to incentivize emissions reductions. This cross-country investigation of the pulp and paper sector yields lower and upper bounds on these shadow prices in the presence of asymmetric capital adjustment. With the combustion of fossil fuels (coal, natural gas, and oil) among the main sources of each type of these emissions, CO₂, N₂O and SO_x are considered in this study.

The empirical results on environmental inefficiency indicate that USA, China, and Ireland are the most environmentally inefficient countries in the pulp and paper sector. Among the significant pulp and paper producers in the world in this sample, all are environmentally inefficient, on average. The notable exceptions are Brazil, France, Germany, India, Japan, Russia, South Korea and Sweden which are environmentally efficient in each year over 1996–2009. Moreover, the results highlight the potential of the USA and China to reduce emissions. The annual reduction of each type of emission in both countries represents, on average, 72.8% of the total sum of each emission reduction in the sample.

Analysis of the shadow prices of net investment and disinvestment suggest that the pulp and paper sector is characterized by asymmetric capital adjustment. In particular, the shadow price of net investment is, in absolute value, greater than the shadow price of net disinvestment implying capital irreversibility and the presence of a “real option” effect. In the presence of sunk costs and demand uncertainty, disinvestments are delayed and firms keep the option value of maintaining capital investments (Kühn & Van Reenen, 2009, p. 400).

Lower and upper bounds on the shadow prices of CO₂, N₂O and SO_x are computed. Shadow prices of pollutants are found to be either positive or negative. A positive shadow price of a pollutant indicates that reducing its emission level implies an economic cost for the industry (i.e., a decrease in the GO, holding the inputs and other emissions constant). Negative prices of a pollutant means that a reduction in its emission level is accompanied by an increase in GO, while keeping the inputs and other emissions constant, implying an economic benefit for the industry.

Based on the price of CO₂ emissions (or CO₂ taxes) computed by OECD (2016), the USA and China have the lowest carbon tax among the largest producers of pulp and paper in the world. The upper bound on the shadow price of CO₂ is lower than the CO₂ tax for the majority of the countries (e.g., Australia, France, Germany, Great Britain, Japan, Turkey, USA). There are a few cases where the upper bound is greater than the CO₂ tax: China, Czech Republic, Estonia and Mexico. If the marginal cost of reducing CO₂

emissions is increasing and strictly convex, the pulp and paper sector in the former (latter) group of countries has incentives to decrease (increase) CO₂ emissions.

Results on the left- and hand-side marginal rate of transformation are, in general, inconclusive with respect to whether emissions are substitutes or complements since the lower bound is negative and the upper bound is positive. This issue needs further investigation probably at a more disaggregated level (e.g., plant level), given its importance for policy design and implementation. Complementarity or substitutability between abatement efforts is fundamental to the choice of policies (Ambec and Coria (2013)).

Besides policy measures, other factors (e.g., technological factors, corporate responsibility) have an important role in explaining the environmental performance of the pulp and paper sector of these countries. Differences in social corporate responsibility across companies and countries are probably another factor to be taken into account when explaining differences in environmental performance. A reasonable range of production technologies have the potential to reduce emissions but available mitigation options are often not fully used due to the presence of barriers like limited access to capital.

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Supplementary materials

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²² Observations of inactivity and investment bursts at the plant level are found in Nielsen and Schiantarelli (2003) for the Norwegian manufacturing and in Cooper and Haltiwanger (2006) for the USA manufacturing.

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