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Jūratė Jaraitė,
Centre for Environmental and Resource Economics,
and Department of Economics,
Umeå University, Sweden

Corrado Di Maria,
Economics and Finance Research Group,
Queen's University Belfast, UK

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Department of Economics, Umeå Universitet
S-901 87, Umeå, Sweden

Efficiency, productivity and environmental policy: a case study of power generation in the EU[*]

Jūratė Jaraitė[†]
Umeå University

Corrado Di Maria
Queen's University Belfast

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Abstract

This study uses the EU public power generating sector as a case study to investigate the environmental efficiency and productivity enhancing performance of the EU ETS in its pilot phase. Using Data Envelopment Analysis methods, we measures the environmental efficiency and the productivity growth registered in public power generation across the EU over the 1996-2007 period. In the second stage of our analysis we attempt to explain changes in productivity and efficiency over time using state-of-the-art econometric techniques. Our analysis suggests two conclusions: on the one hand carbon pricing led to an increase in environmental efficiency and to a shift outwards of the technological frontier; on the other hand, the overly generous allocation of emission permits had a negative impact on both measures. These results are shown to be quite robust to changes in controls and specifications.

JEL Classification: O38, Q48, Q58

Keywords: Emissions Trading, EU ETS, Environmental Efficiency, Productivity Growth, Data Envelopment Analysis

1 Introduction

Reducing the risk of catastrophic climatic change requires the stabilisation of the concentration of green-house gases (GHGs) to 450-550 parts per million (ppm) of carbon dioxide equivalent – a level considered consistent with an increase in average temperatures not exceeding 2 degrees centigrade (IPCC, 2007). There is little doubt that achieving such a target is a daunting task that requires a complete paradigm shift in the long-run. In particular, the transition towards carbon-free energy sources is paramount if this objective is to be achieved. Focussing on power generation, however, there is no doubt that an

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[†] Corresponding author: Centre for Environmental and Resource Economics (CERE), Department of Economics, Umeå Univeristy, Sweden. e-mail: `jurate.jaraite@econ.umu.se`

effective climate change mitigation strategy for the short and medium run calls for the production of energy in the most efficient possible way. Therefore, the role of mitigation policies is to create incentives to follow carbon reducing practices, to develop and adopt new technologies, and, more in general, to increase the overall efficiency of power generation. The latter is the focus of this paper.

We study the productive and environmental efficiency of fossil-fuel based public power plants across member states (henceforth MS, for brevity) of the European Union (EU) over the twelve-year period (1996-2007) that spans the ratification of the Kyoto Protocol and the first three years of the European Union's CO_2 Emissions Trading Scheme (EU ETS). The main focus of our analysis is whether improvements in terms of environmental efficiency and productive performance in the energy generating sector in the EU have occurred, and if so, whether it is possible to attribute such changes to climate change mitigation policies, controlling for other contributing factors.

We focus on the EU ETS as it represents the largest cap-and-trade system currently operating in the world, and it constitutes the centrepiece of the EU climate policy. As more efforts are underway to introduce similar policies in other countries, answering the questions posed above is of fundamental importance to inform the debate on the design of effective policies aimed at reducing the carbon footprint of energy generation. The fossil-fuel based power generating sector is also a natural choice as it is the largest sector in the EU ETS in terms of emissions, being responsible for roughly one third of the total amount of GHG produced by the EU. Power generation is also particularly interesting for other reasons. As discussed by Widerberg and Wråke (2009) and Ellerman et al. (2010), the perception that more low-cost abatement opportunities were available in power generation than in other sectors, and the fact that the sector is not directly exposed to international competition were the main reasons why power generation faced more stringent regulation having received relatively fewer allowances than other sectors elsewhere in the EU ETS. This, we contend, makes the EU power generating sector a good case study as it holds important lessons for a not too distant future when stringent market-based regulation might be much more widespread than at present.

The literature emphasises two characteristics of marketable pollution permits that are relevant to our efforts: on the one hand, like all other market-based instruments, they are capable of bringing about pollution reductions at least cost (Montgomery, 1972; Tietenberg, 1990, among others); on the other hand they have the potential to induce the development and/or the adoption of improved pollution-adoption technologies (Milliman and Prince, 1989; Jaffe et al., 2003; Stavins, 2003; Requate and Unold, 2003). Through both channels, one would expect emissions trading to enhance the environmental efficiency of regulated firms.

Despite the obvious relevance of the topic, few studies so far document empirically the environmental performance of the EU ETS. Ellerman and Buchner (2008) and Anderson and Di Maria (2010) provide ex post analyses of the first trading phase of the EU ETS. Ellerman and Buchner (2008) find that between 130-200 Mt of CO_2 were abated in 2005 and 140-220 Mt in 2006 for all EU member states. Anderson and Di Maria (2010) improve on these results using more refined data for 2005-2007 and estimate overall abatement at 247 Mt CO_2 over the entire first phase. Delarue et al. (2008) and Widerberg and Wråke (2009) explicitly focus on abatement in power generation. Delarue et al. (2008) analyse the European power sector's CO_2 short-term abatement possibilities through fuel switching. Using both a non-calibrated and a historically calibrated simulation models the authors' estimates of abatement range between 34.4 and 63.6 Mt of CO_2 in 2005, and 19.2 and 35

Mt in 2006. Widerberg and Wråke (2009) look at the effect of the carbon price on the CO_2 emissions intensity of the Swedish electricity sector for the period 2004-2008. They find no statistically significant link between the price of EUAs and CO_2 emissions, and conclude that it is unlikely that there are significant volumes of low-cost CO_2 abatement possibilities with short response times in the Swedish electricity sector, which might be explained by the peculiar characteristics of the Swedish system.

Our paper contributes to this sparse empirical literature by assessing the impact of the EU ETS on the power generation sectors using macro-level data for 24 European countries. In order to do so, we develop measures of environmental efficiency and overall productivity applying Data Envelopment Analysis (DEA) methods. We then use econometric techniques to estimate the effect of the EU ETS (in terms of carbon price and policy stringency at the national level) on both indicators, controlling for other relevant variables. We find that the EU ETS had a positive effect on the environmental efficiency of the European public power generation, and that the laxity of the policy – as measured by the degree of overallocation of permits – operated in the opposite direction, partially or even completely offsetting the policy benefits. Our results further show that while the EU ETS didn't seem to affect the overall productivity of public power plants, it significantly affected its two components: technological change and technical efficiency change. The pricing of CO_2 triggered an upward shift of the generation frontier, while the generous allocation of permits tended to offset this effect. Overall, our results conforms to the theoretical expectations about cap-and-trade systems in that the pricing of emissions is shown to be performance enhancing. However, our analysis crucially emphasizes the potentially negative impacts that flaws in the scheme design may have on efficiency and productivity.

The rest of the paper proceeds as follows. Section 2 presents the methodology used to measure environmental efficiency and productivity of public power generation. Section 3 presents and briefly discusses the measures of environmental efficiency and productivity change. Section 4 describes the conceptual framework and the data employed to analyse the determinants of environmental efficiency and productivity change over time. Sections 5 and 6 present the results of the second stage and, finally, section 7 concludes.

2 Measurement of environmental efficiency and productivity

To measure the environmental efficiency and the overall productivity of the power generating sector across EU member states, we develop measures based on data envelopment analysis (DEA) techniques. Our use of DEA is dictated by the flexibility and the robustness of this methodology. DEA assigns scores to decision-making units (or, in our case, to entire productive sectors) on a scale between 0 and 1, depending on how efficiently they convert inputs into outputs. In other words, DEA estimates a 'best-practice' frontier given the available information, and then places each observation on or below the frontier, based on its relative efficiency. This has several advantages from our point of view. First, DEA, as a nonparametric method, only needs to assume that the available observations belong to the same production possibility set, which is a prerequisite for comparability, without imposing any additional structure. This is clearly an advantage given that we use industry level data, and given the diversity of the power generating sector across the EU. Indeed there are large differences among EU MS with respect to the type of technology installed, the fuel mix, and the extent of cogeneration, for example. Such a variety of structures would pose serious classification problems within a parametric framework. Secondly, as DEA highlights best rather than average practice, it is better suited to analyse a semi competitive sector such as power generation where average performers may be well in the interior of the production possibility set. The multi-input/multi-output specification of the technology also increases the informational value of the benchmarking, in addition to the avoidance of a priori assumptions on the production possibility set. Thirdly, DEA allows for a variety of substitution possibilities among inputs and outputs that cannot be captured by parametric methods. In particular, by allowing the inclusion of negative outputs like pollution, DEA is extremely useful when discussing environmental performance, given that the same level of efficiency may be achieved by increasing good-outputs or reducing bad ones. Finally, the nonparametric models are easy to compute and most of their statistical properties are well established through use of bootstrapping methods.[1]

2.1 Using DEA to measure relative efficiency

Consider a production process in which desirable and undesirable outputs are jointly produced by consuming inputs. Let $\mathbf{x} \in \mathbb{R}^N_+$, be the N-dimensional vector of inputs, and $\mathbf{y} \in \mathbb{R}^M_+$ and $\mathbf{u} \in \mathbb{R}^J_+$ the vectors of desirable and undesirable outputs (pollutants), respectively. The production possibility set for this technology is

$$T = \{(\mathbf{x}, \mathbf{y}, \mathbf{u}) | \mathbf{x} \, \text{can produce} \, (\mathbf{y}, \mathbf{u})\}. \tag{1}$$

T provides a complete description of all technologically feasible production plans, and is assumed to be a closed and bounded set, which guarantees output closeness, implying that finite amounts of inputs can only produce finite amounts of outputs. In addition, inputs and desirable outputs are assumed to be strongly disposable. Given the joint production of both desirable and undesirable outputs, we assume null-jointness in production[2] and, at least initially, weak disposability of the outputs. The latter assumption proves not to hold in our dataset and we hence opt for strong disposability for the outputs.[3]

Observing a sample of K entities whose relative environmental and overall technical efficiency are to be measured, and letting the observed data on inputs, desirable and undesirable outputs for each entity k=1,...,K be $\mathbf{x}_k$=(x_{1k},...,x_{Nk}), $\mathbf{y}_k$=(y_{1k},...,y_{Mk}) and $\mathbf{u}_k$=(u_{1k},...,u_{Jk}), respectively, (1) can be expressed within a DEA framework as

$$T = \left\{ (\mathbf{x}, \mathbf{y}, \mathbf{u}) \;\middle|\; \begin{array}{l} \sum\limits_{k=1}^{K} \lambda_k y_{mk} \geq y_m, \; m = 1, \ldots, M, \; \sum\limits_{k=1}^{K} \lambda_k u_{jk} \leq u_j, \; j = 1, \ldots, J, \\ \sum\limits_{k=1}^{K} \lambda_k x_{nk} \leq x_n, \; n = 1, \ldots, N, \; \lambda_k \geq 0, \; k = 1, \ldots, K \end{array} \right\} \tag{2}$$

---

[1] See Fried et al. (2008) for a thorough review of DEA and other methods of productivity analysis.

[2] Null-jointness simply captures the idea that the only way to completely eliminate undesirable outputs is to cease production altogether. Formally, it is defined as: if $(\mathbf{x}, \mathbf{y}, \mathbf{u}) \in T$ and $\mathbf{u} = 0$, then $\mathbf{y} = 0$.

[3] We estimated the environmental efficiency scores assuming alternatively weak and strong disposability. The resulting estimates were indistinguishable from each other, and we thus opted for strong disposability. The fact that CO_2 and SO_2 appear to be *privately* strongly disposable is not surprising, given the absence of regulation on carbon emissions until 2005, the ease with which costs are passed through to consumers in European energy markets, and the predominantly command-and-control nature of SO_2 regulation.

Note that the convexity constraint $\sum_{k=1}^{K} \lambda_k = 1$ is not included in the above model, as we assume constant returns to scale (CRS), and that, as discussed above, undesirable outputs are assumed to be strongly disposable. We assume that the returns to scale are constant given that we focus on aggregate data at the sectoral level across different countries over time and as such assuming variable returns to scale doesn't seem meaningful (See Coelli and Rao, 2005, for a more detailed discussion on this aspect).

On the basis of (2), we introduce the following non-radial DEA-type programming model for calculating the environmental efficiency performance index for entity i:

$$\begin{aligned} ENV(\mathbf{x}_i, \mathbf{y}_i, \mathbf{u}_i) = \min \quad & \tfrac{1}{J}\textstyle\sum_{j=1}^{J} \theta_j \\ s.t. \quad & \sum_{k=1}^{K} \lambda_k y_{mk} \geq y_{mi},\ m = 1, \ldots, M, \\ & \sum_{k=1}^{K} \lambda_k u_{jk} \leq \theta_j u_{ji},\ j = 1, \ldots, J, \\ & \sum_{k=1}^{K} \lambda_k x_{nk} \leq x_{ni},\ n = 1, \ldots, N, \\ & \lambda_k \geq 0,\ k = 1, \ldots, K; \end{aligned} \tag{3}$$

where the λ_k's are coefficients representing the intensity levels for entities in the construction of the reference efficiency frontier. This model can be seen as a Russell-type DEA model in the context of environmental efficiency measurement (Färe et al., 1985). Examples of similar recent models in the context of environmental or energy efficiency measurement include Picazo-Tadeo and García-Reche (2007) and Zhou and Ang (2008).

It is worth noting that (3) non-proportionally adjusts undesirable outputs for given levels of the inputs and the desirable outputs. As a result, it allows some undesirable outputs to increase so that other undesirable outputs achieve larger reductions in order to reach its ideal bench-marking point on the best-practice frontier. Since ENV is essentially the minimum average of the ratios of the expected undesirable outputs to the actual undesirable outputs, we may refer to ENV as an average environmental performance index.

In this programme the input constraints guarantee that, at the optimum, entity i will make use of no fewer inputs than the efficient productive entity it is compared with. The desirable output constraints ensure that under its environmentally efficient production plan, entity i produces no more desirable outputs than the technological reference at the frontier, while the undesirable output constraints make sure that, at the optimum, entity i does not pollutes less than the efficient productive entity it is compared with. The inequality constraints on desirable and undesirable outputs finally imply that both are freely disposable.

2.2 Using DEA to measure productivity changes

To measure the overall technical efficiency we introduce the following model,

$$
\begin{aligned}
ECON(\mathbf{x}_i, \mathbf{y}_i, \mathbf{u}_i) = \min \quad & \phi \\
s.t. \quad & \sum_{k=1}^{K} \lambda_k y_{mk} \geq y_{mi},\ m = 1, \ldots, M, \\
& \sum_{k=1}^{K} \lambda_k u_{jk} \leq \phi u_{ji},\ j = 1, \ldots, J, \\
& \sum_{k=1}^{K} \lambda_k x_{nk} \leq \phi x_{ni},\ n = 1, \ldots, N, \\
& \lambda_k \geq 0,\ k = 1, \ldots, K,
\end{aligned}
\tag{4}
$$

This programme adopts Farrell's (1957) radial input-oriented measure of technical efficiency to measure the performance of energy producing entities at given points of time, and as such ϕ measures how much the inputs and the undesirable outputs can be reduced while maintaining desirable outputs at their original level. As a consequence, it only conveys information that refers to the distance from the frontier (i.e. entity i's relative technical efficiency). For our purposes, it is desirable to have information also on the way the efficient frontier shifts over time, to assess the extent of technological change. Several indexes are available for this purpose, in the present context, given the assumption of CRS and the fact that the data support the strong disposability of pollutants at the aggregate level, we use the Malmquist Productivity Index (MPI) developed by Caves et al. (1982) and extended by Färe et al. (1994). The MPI provides information on productivity over time and allows us to decompose overall productivity changes into its two components of technical efficiency, i.e. distance to the frontier within each period, and technological change, i.e. shifts of the frontier over time.

The input-oriented Malmquist productivity index for entity i, between periods s (the base period) and t, is given by[4]

$$
M^I_{it}(\mathbf{y}_{it}, \mathbf{x}_{it}, \mathbf{y}_{is}, \mathbf{x}_{is}) = \left[\frac{D^I_{is}(\mathbf{y}_{it}, \mathbf{x}_{it})}{D^I_{is}(\mathbf{y}_{is}, \mathbf{x}_{is})} \times \frac{D^I_{it}(\mathbf{y}_{it}, \mathbf{x}_{it})}{D^I_{it}(\mathbf{y}_{is}, \mathbf{x}_{is})} \right]^{1/2}, \tag{5}
$$

where the superscript I indicates input-orientation and M is the productivity of the most recent production point $(\mathbf{x}_{it}, \mathbf{y}_{it})$ (using period t technology), relative to the earlier production point $(\mathbf{x}_{is}, \mathbf{y}_{is})$ (using period s technology). The D's are Shephard input distance functions (Shephard, 1953), and all other variables are as previously defined. Values greater than unity indicate positive productivity growth between the two periods. An equivalent way of writing this productivity index is

$$
M^I_{it}(\mathbf{y}_{it}, \mathbf{x}_{it}, \mathbf{y}_{is}, \mathbf{x}_{is}) = \frac{D^I_{it}(\mathbf{y}_{it}, \mathbf{x}_{it})}{D^I_{is}(\mathbf{y}_{is}, \mathbf{x}_{is})} \left[\frac{D^I_{is}(\mathbf{y}_{it}, \mathbf{x}_{it})}{D^I_{it}(\mathbf{y}_{it}, \mathbf{x}_{it})} \times \frac{D^I_{is}(\mathbf{y}_{is}, \mathbf{x}_{is})}{D^I_{it}(\mathbf{y}_{is}, \mathbf{x}_{is})} \right]^{1/2}. \tag{6}
$$

The ratio outside the square brackets measures the change in the input-oriented measure of technical efficiency between periods s and t, i.e. the efficiency change is equivalent to the ratio of the technical efficiency in period t to the technical efficiency in period s. The remaining part of the index is a measure of technical change[5] as measured by shifts in the frontier measured at period t and period s (the geometric mean of the two ratios in the square bracket).

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[4] Note that here undesirable outputs are treated as inputs.

[5] Note that the change could be in either directions indicating technological progress or regress.

Table 1: Descriptive statistics of outputs and inputs

Variable	Unit	Mean	Std. dev.	Min	Max	No. of obs.	Data source
Power generation	ktoe	7,318	506	569	39,679	288	Eurostat
Fuel	ktoe	15,346	1128	996	89,896	288	Eurostat
Installed capacity	MW	15,382	1080	569	71,072	288	Eurostat, IEA
Labour	Thousands	58	4	5	255	288	Euromonitor International
CO_2 emissions	kt	55,214	4,245	1910	345,673	288	EEA
SO_2 emissions	kt	241	18	1	1361	280	EEA

Provided that a suitable panel data set is available, the distance measures for the Malmquist productivity index can be calculated using DEA-like linear programs as discussed, for example, by Färe et al. (1994) who make use of the fact that Shephard's input (output) distance functions are the inverse of the corresponding Farrell measures of technical efficiency, presented in (4). For the each entity i, four distance functions need to be calculated to measure the productivity change between two periods, s and t. This requires solving four linear programming problems like (4) for each entity in the sample.

2.3 Measuring environmental efficiency and productivity

To compute aggregate measures of environmental efficiency and productivity change in the EU, we construct an industry level dataset covering twenty-four EU member states over the period 1996-2007.[6] We focus on public power plants - public thermal power plants and district heating plants - that mostly rely on combustible CO_2-intensive fuels, such as oil, solid fuels and gas.[7] We aggregate gross electricity generation and gross heat production from public thermal power plants and district heating plants to obtain one (desirable) output variable measured in thousands tonnes of oil equivalent (ktoe).

The production of electricity and heat in this sector also produces undesirable outputs in the form of emissions of pollutants. We collect data on CO_2 emissions from public electricity and heat production from the European Environmental Agency (EEA). According to the Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 1996), these emissions correspond to the sum of emissions from public electricity generation, public combined heat and power generation, and public heat plants. CO_2 emissions are measured in thousands of tonnes (kt). We also include SO_2 emissions among the undesirable outputs. These are also available from the EEA and are measured in kt. SO_2 emissions are not available for Poland and Slovenia until 2000.

Given the constraints on the number of input variables that can be used in DEA analyses, we only consider three types of inputs: labour, fuel inputs, and net installed electrical capacity.[8]

We construct our labour data using employment data provided by Euromonitor Inter-

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[6] Cyprus, Luxembourg and Malta are excluded from the sample due to issues of data unavailability and the fact that these countries are very small compared to the other countries in the sample.

[7] According to the Eurostat definitions, public thermal power stations can be either in public or private ownership and generate electricity and/or heat for sale to third parties as their primary activity. District heating plants produce heat used for process or space heating in any sector of economic activity including the residential sector. Only heat sold to third parties is included in the series.

[8] As a rule of thumb, it is usually suggested that in order to achieve a satisfactory balance between efficient and non-efficient entities there the number of decisions making entities should be three times as large as the sum of inputs and outputs (see e.g. Nunamaker, 1985).

national. Starting from the economically active population in the electricity, water and gas supply industry (ISIC-68, division 4), we take employment in public power plants in each country and each year to equal the share of such total employment that corresponds to the share of total output (electricity and heat) accounted for by public power plants. While this is a rough estimate, we are comforted by the fact that by far the largest share of employees ascribed to division 4 belongs to the subdivision "Production and distribution of electricity".

Fuel inputs are measured in ktoe, and include all varieties of fuel utilised by public power plants: solid fuel, crude oil and petroleum products, renewable energies, and biofuels. As fuel input data are available in the same measurement units, they were aggregated into one indicator.

We use net installed generating capacity as a proxy for the stock of capital.[9] Eurostat provides the net installed electrical capacity data for thermal power plants only, i.e. there is no separation between *public* thermal power plants and *autoproducer* thermal power plants. This distinction is instead made by the IEA, but it is only available for the OECD countries in the sample. We use IEA data whenever available, while for the remaining 6 member states (Bulgaria, Estonia, Latvia, Lithuania, Romania, Slovenia) we use the Eurostat data on net installed capacity of all thermal power stations as a proxy for the net installed capacity of *public* thermal power plants. We believe this is a reasonable approximation given that the share of energy generated by public thermal power plants is very high for these countries.[10]

3 Environmental efficiency and productivity measures

The average environmental efficiency scores for CO_2 and SO_2 emissions over the period 1996 to 2007 are reported in Table 6, where countries are listed in decreasing order of relative environmental efficiency in 2007. A second set of scores were also estimated, including CO_2 and SO_2 emissions separately. For the sake of brevity these results are summarised in Figure 3 below.[11]

Our estimates suggest that substantial reductions in CO_2 and SO_2 emissions are possible in most countries. In 2007, for example, the average environmental efficiency score was 0.39 implying that it could be possible to reduce emissions of these air pollutants by 61 per cent on average, while maintaining inputs and desirable outputs at their current levels. This potential for emissions reduction in fossil fuel based power generation reflects the wide range of different technology and fuel mix currently in use across the EU, and to an extent confirms the conventional wisdom according to which some of the largest and cheapest GHG emission reductions could be achieved in the power generating industry (see CEC, 2009, for example).

Environmental efficiency scores vary across countries reflecting the fuel mix used in power generation. For instance, in 2007, the average relative environmental efficiency for countries relying mostly on natural gas (i.e. in our definition those where the share

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[9] The net capacity is the maximum power that can be supplied, continuously, with all plant running, at the point of outlet to the network.

[10] Capacity data are not available for Bulgaria before 1998. However, electricity data are available for all period of interest. Given that electricity generation data show no significant variations in the electricity production in 1996 and 1997, we use capacity data from the first available year (1998) for the missing years.

[11] The complete set of results is available from the authors upon request.

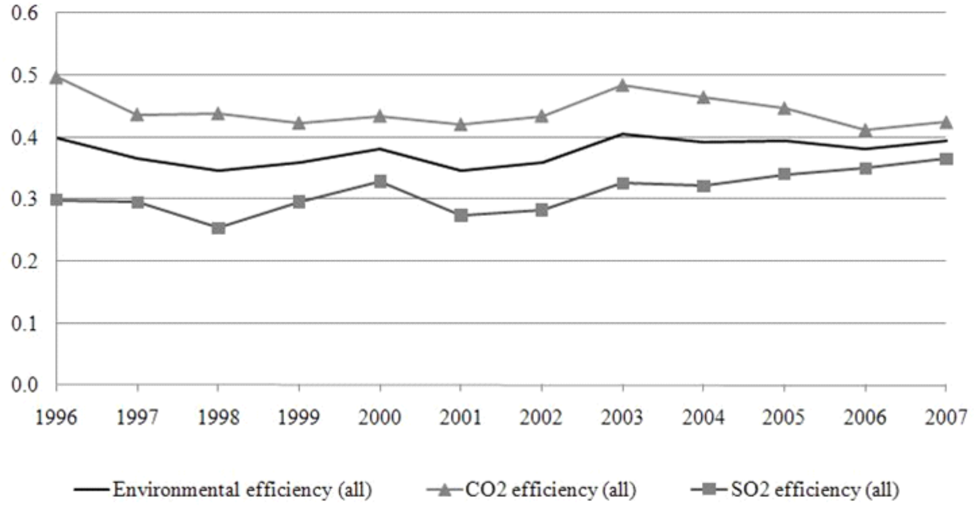

Figure 1: Mean environmental efficiency scores

of gas in the fuel mix is larger than 50 per cent in 2007) is twice as large as the relative environmental efficiency of countries whose energy generating sector is more coal-based (see Table 6). The average environmental efficiency of gas-based power generation has been increasing since 1996 and it visibly improved in the years of the first trading period of the EU ETS. The opposite is true for coal-based power generating industries.[12]

Table 7 presents the annual increases in MPI for all countries in our sample over the 1996-2007 period. Countries are presented in descending order of magnitude of the cumulative MPI changes over 1996-2007. The confidence intervals derived from the bootstrap show that the annual changes are significant for most of the countries.[13]

Figure 2 shows the mean cumulative MPI measure and its components - Technological Change (TC) and Technical Efficiency Change (EC) over the period 1996-2007.[14] On average, the MPI change in the European public power generating industry was positive: the average twelve-year cumulative MPI growth across all countries was 9.7 per cent (0.8 per cent per annum).

Finland, Sweden, Slovakia, Portugal and Spain are the countries that experienced the biggest growth in productivity since 1996, according to our MPI measure. Table 7 also indicates significant country variations among EU member states. We can clearly observe that most of the productivity improvements occurred in the EU15 member states (e.g. the average cumulative MPI was 16.9 per cent over the period of our analysis) rather

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[12] Notice that, while a direct comparison across years is not straightforward, as efficiency scores are relative to the best performing power generating industries in each year, the fact that most countries remain on the frontier over the period of interest justifies our interpretation.

[13] Although the nonparametric MPI measures are taken to be deterministic, they measure performance relative to an estimate of the true and unobservable production frontier. Since estimates of the production frontier are based on finite samples, efficiency and productivity measures based on these estimates are subject to the sampling variations of the frontier. It is therefore necessary to assess the sensitivity of MPI with respect to this sampling variation by bootstrapping the indices. We apply the bootstrapping algorithm developed by Simar and Wilson (1999) to estimate the sampling distribution and confidence intervals for the Malmquist productivity indices. Simar and Wilson (2008) present a comprehensive discussion about statistical inference in nonparametric frontier models.

[14] The full output of the DEA procedure, including the decomposition of the MPI in Technical Efficiency Change and Technological Change following (6), is available from the authors upon request.

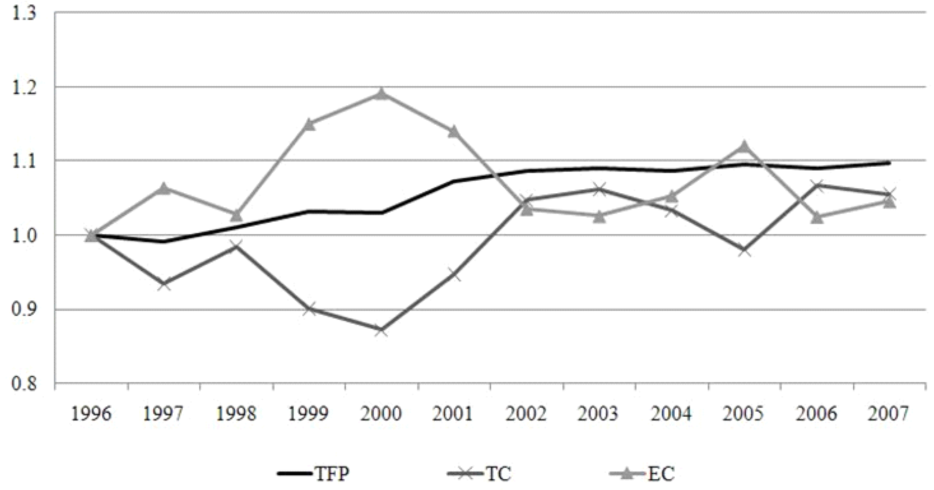

Figure 2: Mean cumulative productivity change, efficiency change and technical change

than in the new MS whose productivity was virtually unchanged.[15] This might mirror differences in structure and developments of power markets between the EU15 and the new MS. The regulated power markets in most of the new MS might not provide enough incentives to increase productivity. For example, the Baltic states, Hungary and Poland all still impose regulated end-user prices for electricity (CEC, 2008), whereas, as shown by Jamasb and Pollitt (2005), the opening up of electricity markets in the EU15 countries seem to have induced an increase in the productivity of electricity companies. On the other hand, this might reflect the fact that the average age of the fossil fuel based power plants in the new MS is much higher than in the EU15 member states suggesting that *per se* older power plants are less efficient (e.g. Graus and Worrell, 2009), and that there might be less incentives to modify these plants during the last years of their life cycle, especially in the context of regulated power markets.

Figure 2 reveals that the major improvements in productivity occurred during 1999-2002. As mentioned above, this can be entirely attributed to EU15 member states. As short-term and long-term fuel switching is incorporated in the DEA estimates by using fuels and capacity as inputs in power generation, it is not surprising to find both periods of technological progress (an upward shift in the frontier technology) and technological regress (an inward shift in the frontier technology) since 1996. In addition to that, the fact that the set of countries shaping the frontier changes over time may also contribute to explain the dynamics of both, the technological change and efficiency change, components.

4 Explaining environmental efficiency and productivity change

Having computed the environmental efficiency scores and the measures of productivity change detailed above, we now turn to econometrically assess whether the introduction of the EU ETS had any impact on these two measures. The censored nature of environmental productivity scores, which are bounded between zero and one, requires some adjustment before we can proceed with the analysis. Inverting the environmental efficiency

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[15] We include among the new MS all countries that accessed the EU in 2004 or 2007.

scores estimated using DEA in the first stage, we obtain an indicator of (the inverse of) environmental efficiency ranging between one and infinity: the larger the value of the transformed environmental efficiency score the lower the degree of environmental efficiency of the sector. Recently, Simar and Wilson (2007) have shown that DEA efficiency coefficients are biased and serially correlated in a complicated, unknown way, making Tobit estimators not appropriate methods for inference. We thus adopt a bootstrapped pooled truncated regression approach to estimate our equation:

$$Y_{k,t} = \alpha_k + \beta \mathbf{Z}_{k,t} + \gamma \mathbf{X}_{k,t} + \epsilon_{k,t}, \tag{7}$$

where $Y_{k,t} \equiv \frac{1}{\theta_{k,t}}$ are the left-truncated average environmental (in)efficiency indicators, $\mathbf{Z}_{k,t}$ is the set of control variables and $\mathbf{X}_{k,t}$ the policy variables of interest. This truncated regression ignores the (unknown) correlation pattern among the residuals $\epsilon_{k,t}$. The presence of α_k indicates that we also include country dummies as they are shown to be significantly different from zero after performing a Wald test.

To explain productivity change and the dynamics of its components, we use linear panel regressions. After performing an F-test, the Breusch-Pagan and the Hausman tests, we select a fixed effects model. Our analysis of MPI change is based on the the following model:

$$MPI_{k,t} = \delta_k + \zeta \mathbf{Z}_{k,t} + \chi \mathbf{X}_{k,t} + \eta_{k,t}, \tag{8}$$

where $MPI_{k,t}$ represents the annual productivity changes, δ_k are the individual country-level effects, $\mathbf{Z}_{k,t}$ are again our control variables, and $\mathbf{X}_k$ the policy variables of interest. Similar specifications are used to analyse the two components of the MPI, TC and EC.

In selecting our controls, we need to take into account that many factors may help explain the variation in the environmental efficiency measures and productivity growth. We include control variables that describe the dynamics of fossil fuel prices, controls designed to capture the sector's technological characteristics such as the fuel mix and the type of technology used, factors that account for the level of economic activity, and variables that control for the possible influence of the endowments of fossil fuels in the country. Our policy variables focus instead on the participation in climate policies directed to mitigate CO_2 emissions (see Table 2 for an overview). We now briefly discuss the potential role of each group of variables in our regressions.

To meet the power demand at the lowest possible cost, power plants are dispatched according to a merit order that depends on production costs. Since fuel costs account for approximately 40 per cent of power generating costs for coal-fired power plants and 60 per cent for gas-based power plants (Graus and Worrell, 2009), it is evident that variations in fuel prices will have significant impacts in the type of fuel that will be used to produce electricity and heat at any given moment in time. Given that gas-based power generation is more efficient both in terms of emissions and energy than coal- or oil-based power generation, fuel prices exert a key influence in shaping the efficient frontier and thus determining the overall environmental efficiency as well as the relative performance of different countries.

Changes in fuel prices drive fuel switching in the short run and investment decisions in the long run. If public power generators have the possibility to switch among fuels in the short run, we can expect environmental efficiency and productivity changes to depend on fuel prices. However, fuel-switching possibilities may be limited, as they crucially depend on the type of generating capacity currently installed, and the characteristics of

Table 2: Overview of variables and data sources

Group of factors	Variable	Data source
Fuel prices	Coal price Crude oil price Natural gas price	Euromonitor International Euromonitor International Euromonitor International
Technological characteristics	Solid fuel share Oil fuel share Gas fuel share Specialisation CHP dummy	Eurostat Eurostat Eurostat Eurostat Eurostat
Economic Activity	Industrial production index FDI to GDP ratio	Eurostat Eurostat
Fossil fuel abundance	Export-TPES ratio	IEA
The EU ETS	CO_2 price Allocation to verification ratio	Point Carbon Community Transaction Log

the electricity market.[16] It is also important to control for these technological and supply factors for other reasons. For example, countries where public power generation has a larger market share could benefit from significant scale economies and have more productive public generators than countries that produce only a small share of power by public power plants. Also, we expect that countries where the share of cogeneration (combined-heat-and-power, CHP) is larger, will be overall more efficient, as CHP typically converts 75-80 per cent of the fuel source into useful energy. In contrast, in conventional separate electricity and heat generation, the overall efficiency is only 60 per cent (IEA, 2008).

Investments in more environmentally efficient capacity take longer to react to changes in prices and policy, and are also determined by the level of economic activity over time and the degree of openness to foreign direct investment. The pace of economic growth may have different impacts on environmental efficiency and productivity. A higher rate of growth might encourage investments in technological innovations and lead to more sophisticated and more efficient plants, or it might stimulate more efficient employment of resources in order to meet the increasing energy demand. On the other hand, a rapid increase in energy demand might only be met using less efficient peak load capacity, which has a detrimental effect on environmental efficiency. Significant inflows of foreign direct investments (FDI) relax the resource constraints of the economy, and might lead to knowledge transfers and knowledge spillovers. In the case of power generation this might initiate the introduction of more productive and more emissions and energy efficient technologies.

The availability of a specific type of fossil fuel in a country is likely to be one of the main determinants of the choice of generating technology, and of the fuel-mix used in public power generation. Conventional wisdom seem to suggest that fossil fuel abundance may be associated with inefficiencies. Hoffmann and Voigt (2009), for example, find that the

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[16] Söderholm (2001) considers various short-run fuel substitution possibilities in Western Europe, and emphasises that fuel switching can occur within a day in dual- or multi-fuel fired plants if the alternative fuel is available, but might take much longer in different circumstance. Also, switching is easier within a firm which owns several power generating units, burning different fuels. Likewise, some conversions of electric plants are relatively easy and cheap – an oil-fired plant that is converted to burn gas, or a coal to oil/gas conversion are examples of this – while other are difficult and expensive.

more hard coal resources a country possesses, the less efficient its electricity generation. On the other hand, it is possible that the willingness to use local, yet polluting, energy carriers might induce specific technological innovation that increase efficiency and overall productivity. The development and deployment of Ultrasupercritical and Integrated Gasification Combined Cycle (IGCC) coal-fired units in Germany represents a good case in point.

The policy we focus on here is the introduction of the emissions trading in the EU in 2005. The emergence of a price for carbon has a very clear effect as it influences the merit order favouring less carbon intensive fuels over more polluting ones. A CO_2 price of 20€/t adds roughly 40 per cent to power generating costs for coal and 20 per cent to power generating costs for gas (Graus and Worrell, 2009). The incentives for producers to switch to cleaner fuels whenever possible are clear. In the medium run, a stable and significant carbon price is expected to drive power generation toward less carbon-intensive technologies (Chen and Tseng, 2008). In the case of the EU ETS, the final impact of carbon emission constraints, however, might depend heavily on the allocation of the EUAs. For instance, an overly generous allocation of permits would weaken the burden of the policy and allow the continued use of carbon-intensive fuels.

4.1 Data description

To control for fuel price dynamics, we use the annual growth rates in the real market prices for coal, crude oil and natural gas. Since country-level fossil fuel prices are not available for all countries in the sample for the whole period, we make use of the same international prices for each country in the sample. As similar strategy is followed by Delarue et al. (2008), who use international prices and claim that the assumption of uniform prices across the EU holds for coal and petroleum products, while it might be questioned for natural gas. On a longer time frame like ours, however, and considering yearly data, there is evidence of convergence in gas prices throughout Europe. The data are taken from the Euromonitor International dataset (see Table 2 for a summary).

Our controls for the technical characteristics of the public power generation sectors across the EU include the proportion of solid fuels, petroleum fuels and gas, respectively, in the total fuel used by public power plants, the share of total electricity produced by public thermal power plants (used as a measure of specialisation), and a dummy variable to account for CHP generation. This latter variable takes the value 1 if the proportion of heat in the total power generated by public thermal power plants exceeds one third, and 0 otherwise.[17] All the series are taken from Eurostat.

Following Hoffmann and Voigt (2009), the variable we use to control for a country's endowment of fossil fuels is the ratio of fossil fuel exports to total primary energy supply (TPES). Fossil fuels include coal and coal products, peat, crude oil, natural gas liquids and feedstocks, and natural gas. The TPES of a natural resource is the production of the resource plus imports, stock changes, and reserves stored in bunkers etc. minus exports. The source of these data is the International Energy Agency (IEA).

As a proxy for the dynamics of economic activity we use the growth rate of the industrial production index, while the ratio of total FDI inflows to GDP is used to measure an extent

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[17] Available data do not allow us to distinguish between power produced by traditional power plants and CHP plants. However, it distinguishes the portions of electricity and heat produced by all (traditional and CHP) power plants. Since only CHP produce heat, we use the share of heat in total power production to proxy for the extent of CHP.

of foreign knowledge transfers and spillovers. Both series are obtained from Eurostat.

As policy variable, we use the average annual price of allowances (taken from the Point Carbon dataset) as an indicator of the overall stringency of the EU ETS. The ratio of the initial permit allocation to verified emissions (taken from the Community Integrated Transaction Log, CITL) is used to capture the country net/short position, which indicates the stringency of the policy for national producers.

Table 3: Descriptive statistics of explanatory variables before transformation, 1996-2007

Variables	Measurement units	Obs.	Mean	Std. Dev.	Min	Max
CO_2 price	€/tCO_2	288	2.86	6.57	0	18.40
Allocation to verification ratio	%	288	25.82	49.33	0	240.81
Coal price	1990 US $/t	288	35.18	9.74	25.32	55.68
Crude oil price	1990 US $/barrel	288	31.17	15.30	12.74	60.24
Natural gas price	1990 US $/MBtu	288	4.08	1.78	2.09	7.57
Export-TPES ratio	%	288	9.59	19.60	0	120.08
Specialisation	%	288	53.42	27.05	3.36	99.02
CHP	1=Yes; 0=No	288	0.43	0.50	0	1.00
Solid fuel share	%	288	52.88	27.40	0.50	98.10
Oil fuel share	%	288	10.55	11.44	0.30	60.20
Gas fuel share	%	288	30.12	20.80	0	80.69
Production index	Index (2000=100)	234	108.53	20.31	71.50	187.97
FDI inflow share	%	253	5.20	5.32	-15.72	34.04

5 The EU ETS and environmental efficiency

Table 4 reports parameter estimates for four different models. Model I features the variables discussed above, but neglects potential non-linearities in the effect that changes in fuel prices may have on environmental efficiency; such non-linearities are, instead, accounted for in Model II. The remaining two columns provide some evidence on the robustness of our results.

The key result emerging from our estimations is that, controlling for a number of relevant factors, the price of CO_2 statistically and positively influences environmental efficiency. This is in line with our theoretical priors and suggests that a process of fuel switching and efficiency improvement was indeed triggered by carbon trading. The second insight to be derived from our results is that the efficiency enhancing effect of carbon pricing was reduced – and possibly offset – by the overly generous allocation of allowances. It is well known that many governments across the EU27 distributed more EUAs than would have been needed, thus reducing the incentive for ETS firms to economise on CO_2 emissions.[18] Our estimates indicate that, with the price of permits averaging above 18 €/tCO_2 during the first two years of the pilot phase, the overall impact of the EU ETS on environmental efficiency was positive. After the price collapse of May 2006, however, the EU ETS might have reduced environmental efficiency.[19]

The other results of Model I in Table 4 also conform to the economic intuition discussed in section 4. An increase in the price of coal leads, *ceteris paribus*, to an improvement

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[18] An excellent reference on this topic is Ellerman et al. (2010), who also provide a thorough overview of the pilot phase of the EU ETS. Evidence of abatement and emissions inflation over the first phase across EU member states is also discussed at length by Anderson and Di Maria (2010).

[19] This is based on the coefficients from Model I. The average allowance price was 18.40 €/tCO_2 during 2005, 18.20 €/tCO_2 in 2006 and a mere 0.72 €/tCO_2 in 2007.

in environmental efficiency, presumably via fuel switching and changes in dispatching due to modifications in the merit order. This is expected given that coal is the least environmentally efficient energy carrier among the ones considered here. Increases in the relative price of oil and gas have opposite impacts, and lead to a reduction in environmental efficiency.

The variables *Specialisation*, *CHP dummy*, and the shares of each fuel in the total fuel used by public power plants are included to capture structural characteristics of energy markets across different countries. The more relevant the role of power public generation, the higher the degree of environmental efficiency, capturing economies of scale, for example. Countries with a share of CHP larger than 33 per cent tend to have a higher efficiency score, reflecting the better environmental performance of this type of technology. The coefficients of the variables indicating the relative fuel shares point to the conclusion that countries that specialise in natural gas tend to enjoy a cleaner energy sector.

The positive sign of the coefficient corresponding to the index of industrial production implies that as economic activity accelerates environmental efficiency drops. This is consistent with the coming on-line of less efficient spare capacity to deal with increased energy demand in the short run. Foreign direct investments, instead, seem to contribute to an increase in efficiency. As discussed above, this might be related to technological transfer or to a relaxation of financial constraints on new investment for local energy generators.

Finally, in terms of the role of the endowment of fossil fuels, our regressions show that the abundance of fossil fuels (as proxied here by the ratio of fossil fuel exports to TPES) is associated with higher environmental efficiency, which is slightly counterintuitive. One possible interpretation, as mentioned above, is that countries with vast reserves of fossil fuels may have stronger incentives to develop cleaner ways to burn them, especially so in the European Union.

It seems likely that changes in fuel prices might have different impacts on environmental efficiency depending on the structure of the power generating sector in different countries. To control for this possible non-linear effects, we estimate a simple variant of our regression model, which includes interaction terms between changes in fuel prices and fuel shares. The estimation of Model II broadly confirms our conclusions on the impact of the EU ETS on environmental efficiency. The only difference is that the lower coefficient associated with the permit price means that, according to this set of results, the EU ETS would not have lead to efficiency improvements in Lithuania in 2005 and 2006, given the very large degree of overallocation experienced by power generators in that country.[20]

Model II allows us to better understand the role of fuel prices on environmental efficiency. For example, it now transpires that an increase in the price of coal leads to an increase in efficiency in countries where coal has a large share in electricity generation (proxied by the share of all solid fuels). This might be due to the fact that intra-coal substitution (from brown to hard coal, for example) is most beneficial, ceteris paribus, when there is a large pool of coal-burning power plants in operation. By contrast, in countries with a large share of oil, a shift away from coal into oil might not be beneficial if the additional oil capacity brought on-line is older and less environmentally efficient, or if the type of oil burned has a higher sulphur content than the coal it replaces. The coefficients for oil and gas prices tell similarly intuitive stories. For example, increases in gas prices lead to

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[20] According to CITL data, the ratio of allocated to verified allowances for Lithuania was 241 per cent in 2005, 199 in 2006 and 197 in 2007.

Table 4: Determinants of environmental efficiency

Dep. Variable: Environmental Efficiency (inverse)	I	II	III	IV
CO_2 price	-0.039***[a]	-0.025***	-0.034***	-0.030***
Allocation to verification ratio	0.003**	0.003***	0.002**	0.002*
Coal price (log difference)*Solid fuel share	–	0.185***	-0.215***	0.178***
Coal price (log difference)*Oil fuel share	–	0.255***	-0.229***	0.247***
Coal price (log difference)*Gas fuel share	–	0.196***	-0.301***	0.189***
Crude oil price (log difference)*Oil fuel share	–	0.288***	0.160***	0.282***
Crude oil price (log difference)*Solid fuel share	–	0.202***	0.107***	0.208***
Crude oil price (log difference)*Gas fuel share	–	0.217***	0.128***	0.218***
Natural gas price (log difference)*Gas fuel share	–	0.066**	0.016	0.043**
Natural gas price (log difference)*Solid fuel share	–	0.071**	0.027	0.046***
Natural gas price (log difference)*Oil fuel share	–	0.074*	0.023	0.050*
Coal price (log difference)	-0.396**	-19.000***	23.953***	-18.321***
Crude oil price (log difference)	0.578**	-20.790***	-10.285***	-20.957***
Natural gas price (log difference)	0.737***	-6.231**	-1.327	-3.620**
Specialisation	-0.023**	-0.015**	-0.020**	-0.022**
CHP dummy	-0.868***	-0.789***	-0.669***	-0.806***
Solid fuel share	-0.015	-0.097***	-0.027	-0.085***
Oil fuel share	-0.011	-0.086***	-0.018	-0.075***
Gas fuel share	-0.087***	-0.179***	-0.102***	-0.168***
Industrial production index (log difference)	3.912***	4.166***	3.868***	–
Industrial production	–	–	–	1.084***
FDI inflow share	-0.027***	-0.018**	-0.022**	-0.031***
Export-TPES ratio	-0.044***	-0.026***	-0.042***	-0.034***
Constant	0.179***	7.902***	2.322***	6.134**
No. of obs.[b]	160	160	160	164
R-squared [c]	0.730	0.717	0.750	0.774

Notes: a. ***, **, and * show significance at 1%, 5%, and 10% respectively. The degree of statistical significance is assessed using confidence intervals computed using the bootstrapping procedure suggested by Simar and Wilson (2007).

b. The number of the observations does not include observations at the truncation point. Greece, Ireland and the Netherlands were dropped from the estimation due to lack of data.

c. The '`truncreg`' command in Stata does not produce R^2, thus, before performing the bootstrapping procedure, we compute a rough estimate of the degree of association by correlating the dependent variable with the predicted value and squaring the result.

declines in efficiency, especially if there is the possibility to switch towards (peak-load) oil-fired capacity, which seem to be the case for a country with a small share of gas in fuel use.

While all of these results are rather intuitive, and the fit of the model satisfactory, we are interested in gauging the robustness of our regression to changes in the set of controls. As a first robustness check, we replace the uniform (world markets) fossil fuel prices by so called "regional" fossil fuel prices, attributing available country-level fuel prices to neighboring countries. [21] These results are reported in column III in Table 4. Despite the change in sign as refers to the impacts of changes in coal prices, our conclusions on the effects of the EU ETS remain unchanged. As a further check, we replace the variable that controls for the level of economic activity – the change in industrial production index – by the level of the industrial production index itself. As can be seen from column IV, also in this case nothing much happens to the EU ETS coefficients.

6 The EU ETS and productivity

Table 5 summarises the estimation results for environmental MPI and its components. Given that the MPI is computed using input-oriented distance functions – see (5) – it makes sense to use the same covariates used in the analysis of environmental efficiency in section 5.

According to the results in Table 5, the EU ETS didn't have overall significant effects on the development of productivity in public power generation. This negative result, however, hides the fact that the estimated impacts of the EU ETS on the components of the MPI are significant but tend to offset each other. In particular, the pricing of carbon leads to a shift in the technological frontier, and increases the TC component, whereas generous permit allocation leads to technological regress – both of which make sense considering technical improvements and merit order considerations, if we accept the premise that gas-based and CHP plants are more efficient overall than coal and oil. The EC component, instead, decreases with the price of carbon. This might be due to the fact that while the frontier shifted out, driven by changes in a subset of countries, efficiency didn't improve as much in most other countries, leading to an increasing productivity gap over time – this effect might be especially marked between old and new member states.

In terms of the effects of changes in fossil fuel prices, we find that an increase in the price of coal leads to a deterioration in productivity. This effect is bigger, the bigger the share of coal-based power generation. This suggests that, for countries that rely heavily on coal, switching to other fossil fuels is difficult. This could lead to tweaking their fuel-mix to favour cheaper types of coal, ultimately leading to technological regress.

The overall effect of an increase in the price of crude oil is to improve productivity. This effect is more likely the smaller the share of gas, and is mostly due to changes in efficiency (EC), rather that shifts in the frontier. This suggest that countries that rely mostly on oil tend to economise on fuel rather than switch away from it, when the price of oil increases.

The coefficients for the change in gas price and the relevant interaction terms suggest that

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[21] As noted earlier, country-level fossil fuel prices are not available for the whole period of interest. Thus, we construct the "regional" prices based on the available country-level data taken from the IEA. Fossil fuel prices (steam coal, high sulphur fuel oil and natural gas) for Finland, France, Germany and France are used to proxy the prices prevailing in neighbouring countries. This is not necessary for Ireland and the United Kingdom as for them a complete set of price series is available.

Table 5: Determinants of ENV productivity change and its components

	MPI[a]	Robust std.err.	Eff. Change[a]	Robust std.err.	Techn. Change[a]	Robust std.err.
CO_2 price	0.0005	0.0007	-0.0019*	0.0011	0.0023**	0.0009
Allocation to verification ratio	-0.0002	0.0001	0.0000	0.0001	-0.0002**	0.0001
Coal price (log difference)*Solid fuel share	-0.0017*[b]	0.001	0.0003	0.001	-0.0020***	0.0005
Coal price (log difference)*Oil fuel share	0.0017	0.0038	0.0013	0.0056	0.0004	0.0025
Coal price (log difference)*Gas fuel share	-0.0013	0.0009	0.0000	0.001	-0.0013**	0.0006
Crude oil price (log difference)*Oil fuel share	0.0053**	0.0024	0.0073**	0.0028	-0.002	0.0025
Crude oil price (log difference)*Solid fuel share	0.0030**	0.0013	0.0052***	0.0014	-0.0022*	0.0011
Crude oil price (log difference)*Gas fuel share	0.001	0.0019	0.0031	0.0032	-0.0021	0.002
Natural gas price (log difference)*Gas fuel share	-0.0022	0.0016	-0.0015	0.002	-0.0008	0.0009
Natural gas price (log difference)*Solid fuel share	-0.0036**	0.0014	-0.0028**	0.0011	-0.0008	0.0011
Natural gas price (log difference)*Oil fuel share	-0.0094***	0.0023	-0.0077***	0.0025	-0.0018	0.0025
Coal price (log difference)	0.1162	0.0923	-0.0067	0.094	0.1232**	0.0576
Crude oil price (log difference)	-0.2789***	0.0958	-0.2756**	0.1199	-0.0041	0.089
Natural gas price (log difference)	0.3375***	0.1096	0.2411**	0.1079	0.0969	0.0826
Specialisation	0.0062***	0.0020	0.0045	0.0029	0.0017	0.0019
CHP dummy	-0.0327	0.0336	-0.0852**	0.0392	0.0529***	0.0183
Solid fuel share	0.0023	0.0023	0.0009	0.0027	0.0014	0.0015
Crude oil share	0.0021	0.0024	0.0006	0.0026	0.0016	0.0016
Natural gas share	0.0016	0.002	-0.0013	0.0023	0.0029	0.0021
Industrial production index (log difference)	0.2944*	0.147	0.3112	0.2484	-0.0173	0.1712
FDI inflow share	0.0006	0.0014	0.0006	0.0017	0.0000	0.0013
Export-TPES ratio	0.0037***	0.0011	0.0011	0.0012	0.0026***	0.0006
Constant	-0.5101**	0.2353	-0.2298	0.3203	-0.2817*	0.1562
No. of obs.[c]	202		202		202	
R-squared	0.23		0.21		0.27	

Notes: *a.* The dependent variables are in logs.
b. ***, ** and * show significance at 1%, 5% and 10% levels, respectively.
c. Greece, Ireland and the Netherlands are dropped from the estimation since some of the data was missing for these countries.

an increase in the price of gas has a positive effect on productivity change via efficiency improvements. However, this effect is dampened if coal- or oil-based capacity is available. Interestingly, this productivity reducing effect comes not from technological regress but from reduction in relative efficiency change.

As in the case of environmental efficiency, the coefficient for specialisation in thermal power plants is significant and positive, implying that more specialised energy sectors tend to be more productive. The growth in industrial production leads to overall productivity improvements. Contrary to what happened in terms of environmental efficiency, here rapid economic growth pushes towards increased productivity in order to meet increased energy demand.

The abundance variable, as in the environmental efficiency model, is significant and positive and suggests that fossil fuel abundant countries are more likely to experience productivity improvements led by technological change. Again, this supports our argument that fossil fuel abundant countries willing to continue fossil fuel based power generation into the future have more incentives to develop better power generating technologies.

Also in this case, we perform the same robustness tests that we discussed in the previous section.[22] All models produce the same signs for the policy variables. In a subset of regressions, however, the country-level stringency variable (*Allocation to verification ratio*)

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[22] The output of the corresponding regressions are available upon request from the authors.

becomes significant in the MPI regression. This supports the idea that, as in the case of environmental efficiency, a generous allocation in the pilot phase tends to depress productivity in power generation. This happens when regional prices are used, as well as when we use the index of industrial production, rather than its growth rate.

7 Conclusions

Trying to assess the environmental and productivity impacts of climate policy measures is crucial if policy makers are to make informed decisions about whether to pursue such policies in the future and how to design them. In this paper we contribute to the scarce ex post quantitative research on the performance of the pilot phase of the EU ETS using the public power generating sector as our case study. The public power sector is the largest sector in the scheme in terms of emissions, and it is also the sector that received the most stringent permit allocation. As a consequence, it is both relevant for the overall appreciation of the effects of emissions trading in the pilot phase, and useful in assessing future developments, as more stringent allocations are to be expected.

Our findings from the analysis of the environmental efficiency and productivity of fossil fuel based public power plants across EU member states emphasise that, although the EU ETS was efficiency improving, the allocation design - the free (over-)allocation of permits - dampened some of these achievements.

We find that even the unstable carbon price in the first phase of the EU ETS, had a positive impact on environmental efficiency. However, overallocation seems to have reduced the benefits of the policy. This effect might have emerged as a consequence of the perceived laxity of the cap for certain, firms or might have been driven by firms trying to inflate their emissions in an attempt to influence second phase allocations.

Looking at productivity change we obtain similar results. While the carbon price did not influence the overall productivity of public power plants, it still had significant effects on the two components of the MPI: a positive effect on technological change and a negative one both on the efficiency change. The policy laxity proxy, instead, only emerges as a significant, negative factor in explaining technological change. Both sets of results prove robust to a number of changes in the regression specification.

Overall, our work lends empirical support to the theoretical view that carbon pricing via emissions trading provides the correct incentives to regulated firms to improve their environmental performance. It also stresses, however, the problems caused by poorly designed allocation rules. By looking at EU power generation in the first phase of the EU ETS, we present a case study of a sector where the scarcity of permits was a very real factor to contend with, at least for most countries, most of the time. In this respect, our results bode well for the future performance of the EU ETS: as future allocations are likely to be much more stringent than they were in the pilot phase, the mistakes of the past will be amended and carbon pricing will lead to further environmental improvements. The lessons learned in this analysis are quite general, as they are derived from analysing several realities with specific individual characteristics, thus they most likely provide useful insights and information to the many regulators currently planning a host of new emissions trading schemes across the world.

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Table 6: Average environmental efficiency scores, 1996-2007

	Base fuel^a	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Austria	Other	1.000	0.747	0.935	0.770	0.649	1.000	0.936	1.000	1.000	1.000	0.858	1.000
Finland	Coal	0.526	0.601	0.391	1.000	1.000	0.349	0.384	1.000	1.000	1.000	1.000	1.000
Latvia	Gas	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Netherlands	Gas	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Sweden	Other	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Denmark	Coal	1.000	1.000	0.385	0.373	1.000	1.000	1.000	1.000	0.853	0.865	0.716	0.699
Hungary	Gas	0.186	0.168	0.182	0.162	0.143	0.162	0.183	0.199	0.210	0.337	0.431	0.452
Lithuania	Gas	0.409	0.390	0.335	0.306	0.327	0.345	0.400	0.503	0.469	0.442	0.439	0.431
Italy	Gas	0.216	0.178	0.177	0.155	0.164	0.213	0.248	0.290	0.313	0.365	0.348	0.429
Belgium	Gas	0.223	0.185	0.215	0.235	0.209	0.235	0.267	0.298	0.266	0.260	0.278	0.338
Germany	Coal	0.219	0.186	0.226	0.205	0.215	0.237	0.263	0.303	0.284	0.276	0.263	0.268
United Kingdom	Coal	0.182	0.161	0.171	0.183	0.156	0.165	0.189	0.201	0.197	0.194	0.180	0.205
Slovakia	Coal	0.298	0.231	0.255	0.202	0.150	0.224	0.218	0.247	0.238	0.223	0.195	0.203
Ireland	Gas	0.180	0.142	0.152	0.132	0.128	0.136	0.163	0.199	0.191	0.167	0.171	0.187
Slovenia	Coal	n/a	n/a	n/a	n/a	0.104	0.109	0.123	0.142	0.133	0.129	0.163	0.174
Czech Republic	Coal	0.242	0.207	0.224	0.341	1.000	0.202	0.187	0.209	0.195	0.172	0.153	0.155
Portugal	Coal	0.170	0.139	0.158	0.141	0.129	0.135	0.153	0.167	0.170	0.157	0.145	0.146
Poland	Coal	n/a	n/a	n/a	n/a	0.147	0.146	0.148	0.163	0.154	0.143	0.128	0.129
Estonia	Coal	0.163	0.139	0.149	0.130	0.117	0.127	0.146	0.146	0.146	0.144	0.135	0.127
Spain	Coal	0.132	0.112	0.117	0.101	0.092	0.098	0.113	0.129	0.130	0.129	0.129	0.127
Romania	Coal	0.229	0.194	0.218	0.176	0.153	0.155	0.147	0.162	0.145	0.127	0.118	0.113
Bulgaria	Coal	0.179	0.119	0.137	0.117	0.100	0.104	0.116	0.128	0.118	0.107	0.099	0.097
France	Other	0.079	0.056	0.079	0.083	0.087	0.098	0.115	0.124	0.116	0.107	0.094	0.095
Greece	Coal	0.117	0.092	0.101	0.090	0.083	0.089	0.100	0.108	0.102	0.092	0.089	0.093
Mean		0.398	0.366	0.346	0.359	0.381	0.347	0.358	0.405	0.393	0.393	0.380	0.394
Mean coal-based		0.288	0.265	0.211	0.255	0.318	0.224	0.235	0.293	0.276	0.268	0.251	0.252
Mean gas-based		0.459	0.438	0.437	0.427	0.424	0.442	0.466	0.498	0.493	0.510	0.524	0.548

Notes: *a*. Indicates the dominant fuel (i.e. a share larger than 50% in the fuel mix) in 2007.

Table 7: MPI annual change and cumulative change for the 24 countries, 1996-2007

Country	Base fuel[a]	96-97	97-98	98-99	99-00	00-01	01-02	02-03	03-04	04-05	05-06	06-07	1996-2007
Finland	Coal	0.944*	0.955*	1.111*	1.001*	1.134*	1.060*	1.213*	0.972*	0.887*	1.205*	1.018*	1.547
Sweden	Other	1.030*	1.064*	0.998*	1.018*	1.103*	1.053*	0.950*	1.029*	1.027*	1.018*	0.991*	1.308
Slovakia	Coal	0.915*	1.133*	0.957*	1.037*	1.282*	0.992*	1.036*	0.979*	0.986*	0.944*	1.047*	1.293
Portugal	Coal	1.010*	1.234*	1.221*	0.925*	0.968*	1.142*	0.807*	1.078*	1.164*	0.854*	0.950*	1.277
Spain	Coal	1.159*	1.040*	1.140*	1.041*	0.933*	1.132*	0.814*	1.019*	1.044*	0.976*	0.998*	1.277
Netherlands	Gas	1.048*	1.078*	0.991*	1.013*	1.054*	1.003*	1.019*	1.034*	1.029*	0.936*	1.018*	1.238
Italy	Gas	1.003*	1.002*	0.990*	0.940*	1.175*	1.049*	0.954*	1.146*	0.979*	1.000*	0.997*	1.231
Belgium	Gas	0.979*	1.008*	1.124*	1.003*	0.966*	1.114*	0.956*	1.003*	0.987*	1.026*	1.031*	1.199
Greece	Coal	1.014*	1.091*	0.957*	1.131*	1.045*	0.943*	0.980*	1.000*	0.917*	0.998*	1.093*	1.156
Austria	Other	0.963*	1.040*	1.012*	0.975*	1.141*	0.971*	1.035*	1.009*	1.064*	0.979*	0.951*	1.135
United Kingdom	Coal	0.992*	1.029*	1.104*	1.002*	1.000*	1.030*	1.000*	0.967*	0.993*	0.986*	1.022*	1.124
Germany	Coal	0.968*	1.041*	0.961*	1.005*	1.052*	0.960*	1.071*	1.014*	1.034*	0.983*	1.032*	1.120
Estonia	Coal	0.993*	0.919*	0.998*	1.010*	1.172*	1.041*	1.079*	0.935*	1.039*	0.981*	0.951*	1.098
Slovenia	Coal	1.075*	1.115*	0.963*	0.959*	0.910*	1.057*	1.033*	1.000*	1.007*	1.010*	0.979*	1.095
Hungary	Gas	1.014*	1.039*	1.043*	0.925*	1.033*	0.946*	1.057*	0.974*	1.023*	0.989*	1.019*	1.055
Ireland	Gas	1.038*	1.012*	1.088*	1.011*	1.045*	0.854*	0.996*	1.005*	0.940*	1.034*	0.985*	0.989
Czech Republic	Coal	0.983*	0.974*	0.966*	1.092*	1.004*	0.956*	1.052*	0.981*	0.968*	0.977*	1.039*	0.985
Lithuania	Gas	1.019*	0.956*	0.967*	0.979*	1.000*	1.021*	1.012*	0.969*	0.983*	1.038*	1.026*	0.966
France	Other	0.926*	1.019*	1.036*	0.950*	0.985*	1.040*	1.002*	1.004*	1.113*	0.906*	0.985*	0.949
Poland	Coal	0.956*	0.979*	0.968*	0.972*	1.024*	0.970*	1.034*	1.008*	0.994*	1.019*	0.972*	0.898
Bulgaria	Coal	0.783	0.968*	0.952*	0.974*	0.897*	0.979*	1.091*	0.988*	1.013*	1.037*	1.246*	0.870
Romania	Coal	1.063*	0.997*	0.930*	1.000*	0.999*	0.959*	0.992*	0.981*	1.014*	0.967*	0.961*	0.867
Latvia	Gas	1.006*	0.936*	0.901*	0.961*	1.080*	0.949*	1.036*	0.935*	1.014*	1.034*	0.986*	0.837
Denmark	Coal	0.886*	0.817*	1.044*	1.086*	1.067*	1.012*	1.083*	0.864*	0.942*	1.096*	0.956*	0.818
Mean		0.990	1.019	1.018	1.000	1.045	1.010	1.013	0.996	1.007	1.000	1.011	1.097
Mean new MS		0.981	1.002	0.965	0.991	1.040	0.987	1.042	0.975	1.004	1.000	1.023	0.997
Mean old MS		0.997	1.031	1.056	1.007	1.048	1.026	0.991	1.010	1.008	1.000	1.002	1.169
Mean coal-based		0.981	1.021	1.020	1.017	1.035	1.017	1.020	0.985	1.000	1.002	1.019	1.102
Mean gas-based		1.015	1.004	1.015	0.976	1.050	0.991	1.004	1.010	0.993	1.008	1.009	1.074

Notes: $*$ denotes indicates a difference from unity at the 1% significance level.

a. "Base fuel" indicates the dominant fuel (i.e. a share larger than 50% in the fuel mix) in 2007.