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The European Union Emissions Trading Scheme and Fuel Efficiency of Fossil Fuel Power Plants in Germany

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Abstract

I investigate the impact of the European Union Emissions Trading Scheme (EU ETS) on fuel efficiency of fossil fuel power plants using administrative micro data on power plants in Germany from 2003 to 2012. I find positive efficiency effects in fuel use, leading to a decrease in fuel input of 0.4 percent for an increase in carbon cost of one Euro. A back-of-the-envelope calculation suggests that the reduction in fuel use by fossil fuel power plants due to the introduction of the EU ETS translates into reductions in annual carbon emissions within the German electricity sector by around seven million tonnes in 2012. This represents about 2.4 percent of total annual carbon emissions in the German electricity sector and exemplifies the potential magnitude of efficiency improvements as a measure for reducing carbon emissions.

Keywords: EU ETS, Carbon Pricing, Fossil Fuel Power Plants, Treatment Intensity

JEL classification: D24, L94, Q48, Q58

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1. Introduction

The energy sector is central to climate protection strategies in several countries including Germany, where it accounts for around 40 percent of total annual carbon emissions. The Intergovernmental Panel on Climate Change (IPCC) states that "[d]ecarbonizing (i.e. reducing the carbon intensity of) electricity generation is a key component of cost-effective mitigation strategies [...]" (IPCC, 2014). Hence, understanding the effects of existing climate policies on the energy sector is crucial for the further development of policies to achieve mitigation targets efficiently.

In this study, I investigate the impact of the European Union Emissions Trading Scheme (EU ETS) on fuel efficiency of fossil fuel power plants in Germany. Furthermore, I analyse potential effects on labour efficiency, investments in machinery and utilization of power plants. The EU ETS is currently the largest cap-and-trade system for greenhouse gas emissions worldwide. It puts a price on greenhouse gas emissions from regulated installations to achieve emission reductions and to provide incentives for investments in low-carbon technologies. As the EU ETS covers multiple sectors, emission reduction efforts within the energy sector will only be undertaken if (marginal) abatement costs are relatively low compared to activities in other regulated sectors and lower than the (expected) market price of emission allowances. Fuel switching, i.e. generating electricity with fuels that are associated with lower (including zero) carbon emissions, is considered as a major option to reduce the carbon intensity of electricity generation (e.g., see the review by Hintermann et al., 2016). However, increasing fuel efficiency may also be an important measure to simultaneously reduce cost and carbon emissions in the energy sector, as emissions are directly linked to fuel use. Hence, studying the impact of the EU ETS on the efficiency of fossil fuel power plants, i.e. choosing inputs to produce a certain output level at minimal cost, allows me to draw conclusions not only on the effect of carbon pricing on the optimal input combination in electricity generation, but also on fuel efficiency improvements as a measure to reduce carbon emissions in the energy sector.

This study employs administrative annual plant-level data from the German statistical offices on nearly all fossil fuel power plants in Germany from 2003 to 2012 (Research Data Centre of the Statistical Offices Germany, 2016). The data encompasses on average about 85 percent of fossil fuel electricity generation in Germany.[1] Germany is particularly suitable for this study because of the size of its energy sector within the EU[2] and its electricity generation structure, consisting of a variety of hard coal, lignite, nuclear, and natural gas power plants as well as renewable energy installations.

[1]The remaining 15 percent is generated by power plants for which participation in the administrative survey is not mandatory. For example, this includes power plants with less than 1 megawatt (MW) bottleneck capacity or industrial power plants that generate electricity only for self-consumption.

[2]Carbon emissions of the German energy sector represent around 30 percent of the European Union's (EU) carbon emissions in the energy sector.

I find positive efficiency effects in fuel use, but no statistically significant labour efficiency effect. An increase in individual carbon cost of one Euro per megawatt hour (MWh) leads on average to a reduction in fuel input by around 0.4 percent, holding the level of output fixed. To put this figure into context, at an average European Emission Allowances (EUA) cost of around six Euro per MWh of electricity and heat generation and assuming a linear effect, the introduction of the EU ETS has lead to an increase in fuel efficiency of around 2.4 percent on average. The rather small magnitude of this effect may be driven by two aspects. First, I also find a negative and statistically significant effect of the EU ETS on utilization of carbon intensive power plants. Lower utilization would be likely negatively associated with fuel efficiency. This exemplifies that the fuel efficiency effect must be interpreted as an overall net effect. Second, this magnitude suggests that rather small scale measures to improve fuel efficiency were implemented. This is consistent with the finding that the effects on investments in machinery are either statistically insignificant or of small magnitude as well as with existing case studies on the investment behaviour under the EU ETS in the German power sector (Hoffmann, 2007; Rogge et al., 2011).

Following Fabrizio et al. (2007) and Gao and Van Biesebroeck (2014), I model the production function in a Leontief fashion to take into account specific characteristics in the underlying production technology for electricity generation. Assuming cost-minimizing behaviour, input demand functions for fuel and labour are derived taking simultaneity of input and output choices into account (e.g. Marschak and Andrews, 1944; Griliches and Mairesse, 1995; Olley and Pakes, 1996).

This framework is used to evaluate the impact of the EU ETS on fuel and labour efficiency. The major identification challenge is that almost all fossil fuel power plants in Germany are subject to this regulation, facing also the same carbon price. This prevents a comparison of treated and untreated plants before and after the introduction of the EU ETS to uncover the causal effect of this policy. However, the EU ETS affects fossil fuel power plants to a different extent depending on emission factors of the fuel used, individual heat rates (ratio of fuel input to generation of electricity and heat) and on the price of emission allowances. Thus, I make use of both cross-sectional and time variation in treatment intensities, i.e. individual carbon cost for electricity and heat generation of plants, to identify the effect of the EU ETS on fossil fuel power plants.[3]

Differences in actual measured heat rates are mainly determined by the state of technology and actual utilization of plants. The technology is determined by investment decisions, i.e. at the time of construction of the plant as well as retrofitting. Investment decisions are thereby based on expectations about development of several different factors, which may include, among others, the structure of the electricity generation sector, future demand and (fuel) cost relationships. The utilization of plants is determined by the level of demand and the plant's marginal cost compared to other (available) plants as well as its maintenance periods. Given these considerations, ETS intensities based on actual measured heat rates are very likely to be endogenous. This potential

[3]In the following text, I will use treatment intensity and ETS intensity interchangeably.

issue is addressed by using a plant-specific measure of ex-ante exposure to carbon prices that relies on actual individual heat rates achieved on average before the introduction of the EU ETS instead of annual ETS intensities. Annual values based on this ETS Ex-Ante Exposure start from 0 Euro per MWh electricity and heat generation (before the introduction of the EU ETS), with the 90th percentile being 15 Euro per MWh for hard coal, 20 Euro per MWh for lignite, and 6 Euro per MWh for natural gas power plants, respectively. Identification relies mainly on within fuel type variation. Within fuel type variation derives from differences in actual achieved heat rates across plants and EUA price changes over time. Thereby, variation across plants of the same fuel type accounts for about 30 to 40 percent of differences in individual carbon cost, with the remaining part resulting from changes over time.

This paper is related to the literature on productivity and efficiency effects from policies and regulation in the electricity generation sector. These studies focus mainly on the effects of deregulation on productivity and efficiency (e.g. Knittel, 2002; Fabrizio et al., 2007; Craig and Savage, 2013; Gao and Van Biesebroeck, 2014). Overall, they find some efficiency gains at different stages of deregulation, e.g. the switch from cost-of-service to incentive regulation (Knittel, 2002) and the turn to competitive markets in the United States (Fabrizio et al., 2007; Craig and Savage, 2013; Chan et al., 2017) as well as in China (Gao and Van Biesebroeck, 2014). This study differs from these papers with respect to the nature of the influence. Deregulation alters the agents' underlying objective function, leading to efficiency changes. In the case of carbon pricing, the objective function remains the same, however, there are (at least) three possible channels through which fossil fuel power plants are affected. First, a price on carbon emissions raises opportunity costs of low heat rates and may therefore incentivize efficiency improvements. Linn et al. (2014) have illustrated this mechanism through the example of coal price changes. This reaction may also depend on (differences in) electricity market regulation as pointed out by Fowlie (2010), who finds that deregulated power plants choose less capital-intensive mitigation measures compared to regulated or publicly owned plants in case of the US NO_X Budget Program. Second, carbon pricing may introduce an additional burden to producers by influencing optimal input combinations. This in turn can lead to negative productivity effects (Gollop and Roberts, 1983) or to higher marginal and total cost (Førsund and Granderson, 2013) as in the case of sulphur dioxide emission regulations. More recently, Zhou and Huang (2016) investigate the effect of the Regional Greenhouse Gas Initiative (RGGI) in the United States on the technical efficiency of power plants. Although they do not find a direct effect of carbon pricing on technical efficiency of regulated power plants, they investigate possible spillover effects on unregulated power plants and find a negative effect. Third, there is evidence that fossil fuel power plants experienced windfall profits from free allocation of emission allowances and carbon cost pass-through under the EU ETS (e.g. Sijm et al., 2006). Modelling results from Pahle et al. (2011) suggest that this could have an effect on investment.[4]

Which of these effects prevail and the size of the resulting net effect of carbon pricing on fuel efficiency are ultimately empirical questions. To tackle these, I analyse the experiences made in an actual introduction of carbon pricing, using administrative micro data on fossil fuel power plants. Despite a relatively large literature of (ex ante) simulation studies, analyses based on aggregate data, or qualitative studies, the empirical literature based on micro data investigating the effect of the EU ETS in the energy sector is still scarce (McGuiness and Ellerman, 2008; Linden et al., 2013; Chan et al., 2013; Yu, 2013).[5] The small number is mainly due to two reasons: lack of detailed micro data and issues in constructing a reasonable counterfactual situation (see e.g. Martin et al., 2016, for a recent review). My paper contributes to this strand of literature addressing both challenges. First, data before the introduction of the EU ETS, especially on fuel input and carbon emissions, is often not available.[6] The data set used in this analysis offers two years of data before the start of the EU ETS in 2005. This allows me to observe power plants before the start of the treatment and use actual measured pre-treatment heat rates in my identification strategy. Thus, it enables me to better isolate the effects actually caused by the EU ETS from other influences.[7] Second and related to the first issue, this paper circumvents the problem of having almost no untreated group of plants in the energy sector by using differences in plant's (ex-ante) treatment intensity for identification. Although this approach to identify effects of comprehensive policies (covering almost all agents in an economy) is in general not new (e.g. Mian and Sufi, 2012), it has not been applied to the energy sector and to the analysis of the EU ETS yet.

The paper is structured as follows: Institutional details on the EU ETS and fossil fuel power plants in Germany are provided in Section 2. Section 3 outlines the empirical model and identification strategy. The data is described in Section 4. Section 5 presents the results and Section 6 concludes.

2. The EU ETS and Fossil Power Plants

2.1. Institutional Background

In 1997, emission reduction targets for the EU were formulated within the Kyoto Protocol. The EU decided to introduce a cap-and-trade system to achieve parts of its obligations (see e.g. in the EU Green Paper published in March 2000). Within a cap-and-trade system, an overall cap on

[4]Windfall profits may be one reason for different results compared to Adair et al. (2014). They find that compliance costs for air regulation crowds out investment in heat rates improvements.

[5]Additionally, there are studies that focus on a variety of sectors, including but not dealing explicitly with the energy sector (e.g. Commins et al., 2011; Löfgren et al., 2013; Jaraite and Di Maria, 2016).

[6]Jaraite and Di Maria (2016), Petrick and Wagner (2014), Löschel et al. (2016) and Lutz (2016) are recent exceptions, where the last three focus solely on the manufacturing sector.

[7]Although, it would have been desirable to include even more pre-treatment years, this data is not available.

emissions for regulated entities is set and emission certificates of an equivalent amount are issued (either by auctioning or free allocation). Regulated entities have to hand in emission certificates in an amount corresponding to their individual annual emissions. Otherwise, they face a penalty for non-compliance. Emission certificates can be traded on a secondary market. By trading emission certificates, marginal abatement costs over regulated entities can be equalized. Thus, the market price should reflect marginal abatement costs given the cap. The EU ETS was introduced in 2005, following the adoption of the EU ETS Directive 2003/87/EC in October 2003. It covers almost 11,000 installations in the energy sector, energy-intensive industry as well as commercial aviation (from 2013 on). Currently, around 45 percent of the EU's greenhouse gas emissions are regulated under this scheme. The EU ETS is divided into different trading phases. This study encompasses Phase I (2005-2007) and Phase II (2008-2012).

The power sector has been included in the EU ETS from the beginning and fossil fuel power plants are in general under regulation of the EU ETS if their rated thermal input is 20 megawatt (MW) or larger. This applies to almost all fossil fuel power plants in Germany. Emission certificates in the first two phases were mainly allocated to power plants free of charge based on their individual historical carbon emissions ("grandfathering"). Average carbon emissions from 2000 to 2002 determined free allocation for Phase I and from 2000 to 2005 for Phase II, respectively. With the start of Phase III in 2013, in general, this grandfathering scheme ended for power plants.[8]

2.2. Power Plants in the EU ETS

In electricity generation, several technologies with different characteristics are employed. Given that electricity cannot be stored economically on a large-scale, supply must always equal demand. Since demand is rather inelastic in the short-run, but varies over time (e.g. hour of day and season), supply has to adjust accordingly. This cannot be fulfilled by a single available technology at least-cost, calling for a mix of several generation technologies with different fixed and variable costs. The employed technologies also differ along other dimensions: in particular, the fuel that is used for electricity generation, and heat rates, which are mainly determined by the underlying technology and vintage.[9] This has implications for the emission intensity of the electricity generation, which varies over individual plants by heat rate and the fuel's carbon content.

Traditionally, the German power generation sector relies heavily on coal. In the period from 2003 to 2012, hard coal and lignite together accounted for more than 45 percent of total generation,

[8] As of from 2013, power plants need to buy their emission certificates either at auctions or on the secondary market. Eight countries (Bulgaria, Cyprus, Czech Republic, Estonia, Hungary, Lithuania, Poland and Romania) are allowed to continue free allocation (by a decreasing amount) to power plants until 2019 under Article 10c of the EU ETS Directive 2009/29/EC.

[9] For example, gas-fired power plants in Germany have an average efficiency rate - the inverse of heat rate, i.e. (gross) electricity produced in energy units with one energy unit of fuel used - of around 50 percent, whereas hard coal fired power plants achieve on average an efficiency rate of around 40 percent (UBA, 2013). But individual heat rates vary among the specifically used technologies. For example, the efficiency rate for a gas-fired power plant is also dependent on whether it is a gas turbine (with a typical efficiency rate of about 40 percent) or a combined cycle gas turbine (CCGT), which additionally uses the waste heat and achieves efficiency rates up to 60 percent.

with each contributing almost equally. In the course of the nuclear phase-out in Germany starting in 2000, the share of nuclear generation in total electricity generation dropped from around 30 percent in the beginning of the 2000's to 15 percent in 2012. Electricity generation from natural gas-fired power plants from 2003 to 2012 varied from around 10 to 14 percent. This time period also exhibited a rise in the share of electricity generated by renewable energy sources, starting from eight percent in 2003 (which was mainly hydro power) to 24 percent in 2012, with wind (8 percent), biomass (6 percent) as well as hydro and solar photovoltaic (each 4 percent) contributing the most.[10]

Generated electricity can be sold either at the wholesale market (day-ahead or forward) or via bilateral trade agreements.[11] The day-ahead wholesale market is widely regarded as a reference for other products (e.g. forward wholesale contracts or bilateral agreements). In this market, plant owners submit hourly supply curves with prices and quantities. The individual bids are aggregated at the market level, with each plant being placed within a merit-order according to its bid. In a uniform price auction, the market price is determined by the intersection of supply and demand.

The individual bidding behaviour[12] and the question whether liberalized wholesale electricity is a competitive or non-competitive market is under ongoing discussion. In a competitive market, plants would act as price-takers, placing bids at their individual marginal cost and would only want to produce electricity whenever the market price was higher than or equal to their marginal cost. When plants do not behave competitively, they try to influence the market price (e.g. by withholding capacity at a price that lies above or equal to their marginal cost). The popular non-competitive models for electricity generation are Cournot (e.g. Bushnell et al., 2008) or Supply Function Competition (e.g. Klemperer and Meyer, 1989; Green and Newbery, 1992). In Germany, installed electricity generation capacity is concentrated to a certain degree: the four largest companies had a share of 58 percent in the German-Austrian market in 2012 (Monopolkommission, 2013). This has raised concerns of potential non-competitive behaviour. The existing evidence of market power in the German wholesale electricity market is, however, inconclusive and at least suggests that behaviour is not stable over time. Müsgens (2006) compares wholesale prices with marginal cost produced by a dispatch model and finds that prices are consistent with competition from the early 2000 to 2001, but differ from marginal cost estimates from 2001 to 2003. Similarly, Weigt and von Hirschhausen (2008) find market prices above competitive levels for 2002 to 2006. However, Möst and Genoese (2009) do not find evidence for non-competitive behaviour for 2006 and neither do Graf and Wozabal (2013) for the period from 2007 to 2010.

[10] The data used in this paragraph stems from the German Federal Ministry for Economic Affairs and Energy (BMWi, 2016).

[11] This applies mainly for electricity generated by conventional power plants. Electricity from renewable energy sources under regulation of the Renewable Energy Sources Act are mainly enjoying priority access to the grid and are paid a fixed-price per generated unit of electricity (feed-in tariff) or a feed-in premium for a certain time period.

[12] In the case, in which actual production decisions are made on a higher level (e.g. company), plants do only have to supply the amount of electricity that is called by the company.

With the introduction of the EU ETS, regulated power plants, which are mainly fossil fuel power plants, are obliged to hand in emission certificates of an amount equivalent to their annual carbon emissions. The emission certificates stem either from free allocation, auctioning, or can be bought on the secondary market. The EU ETS is expected to impact fossil fuel power plants by raising marginal production cost and generating windfall profits due to cost pass-through and free allocation of emission certificates.[13] Introducing a carbon price means that emission is now costly for the plant (even if the emission certificate is allocated for free to the power plant, it represents an opportunity cost) and thus, the carbon content in the fuel raises input costs for fuel. Dependent on the emission intensity of the fuel used for electricity generation, this additional cost can be significant as it is shown in Figure 1 based on data from BAFA (2015a; 2015b), UBA (2013) and from the European Energy Exchange (EEX).

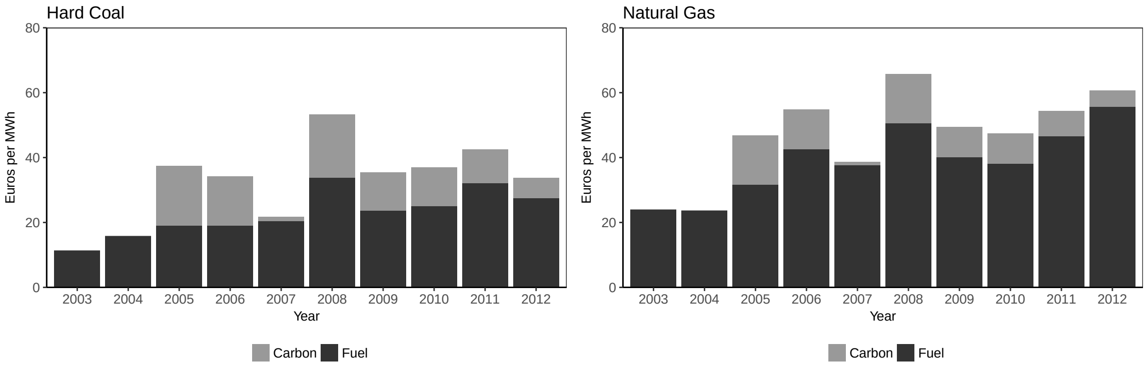

Figure 1: Average Fuel and Carbon Cost in Power Generation

Notes: The black bars represent the average fuel cost to generate a megawatt hour electricity in each year from 2003 to 2012 of a hard coal power plant (left panel) and a natural gas power plant (right panel), respectively. The grey bars illustrate analogously the average carbon cost. Own calculations based on data from BAFA (2015a; 2015b), UBA (2013) and EEX.

Under marginal cost pricing, emission costs are expected to be completely incorporated in the power plants' bids, leading to an emission cost pass-through onto the electricity price. However, demand reactions and non-competitive behaviour could also lead to an incomplete pass-through of emission costs. The empirical literature on cost pass-through of emission costs within the EU ETS to wholesale electricity prices in Germany suggests that emission cost are almost completely incorporated in the bids and passed onto the electricity price. An early study by Sijm et al. (2008) finds incomplete pass-through rates. While these estimates depend on the relationship between electricity prices and input prices, it is marginal input cost that matters for cost pass-through, i.e. taking into account the marginal plant's emission intensity in addition to carbon prices

[13] Another impact of the introduction of the EU ETS is the trading of emission certificates. However, since this is mainly done at the company level (e.g. Heindl and Lutz, 2012) and the energy sector is in general experienced with (commodity) trading, I abstract from this issue in the following.

(Hintermann, 2017; Fabra and Reguant, 2014). k Hintermann (2017) finds that in the period from 2010 to 2013, emission costs are on average (almost) completely passed through to the electricity prices in Germany, with the extent differing by the level of aggregate demand. This is in line with Fabra and Reguant (2014), who find almost complete pass-through in Spain from 2004 to 2006, using detailed bid-level data. Zachmann and von Hirschhausen (2008) and Mokinski and Wölfing (2014) find evidence for asymmetric cost pass-through in 2005 and 2006 to wholesale electricity prices in Germany. This asymmetric pass-through ends, however, in early 2006 at the same time as investigations of pricing behaviour by the German competition authority became public (Mokinski and Wölfing, 2014).

The incorporation of carbon cost and the associated increase in marginal generation costs affect power plants to a different extent potentially affecting operational decision (McGuiness and Ellerman, 2008) and fuel substitution (Linden et al., 2013). For the first two years of the EU ETS, McGuiness and Ellerman (2008) find a positive impact on the utilization of natural gas power plants in the United Kingdom, whereas coal power plants experienced a lower level of utilization consistent with the higher carbon costs that these plants have to bear. On the other hand, Linden et al. (2013) find that fossil fuels even within a plant are replaced by wood in Sweden. However, this may be a particularity of the Swedish electricity sector and is not (yet) a current practice in the German electricity sector. Furthermore, it is unclear to which extent this reflects already existing trends as pre-treatment years are not observed. Commins et al. (2011) observe lower total factor productivity in the power sector compared to non-regulated sectors after the introduction of the EU ETS.

The EU ETS might not only affect individual operational decisions but also investment decisions. These include market entry, i.e. building a new power plant and deciding on size (capacity) and technology (heat rate and fuel type), but also investments in existing plants. For example, heat rate improvements may be incentivized by raising opportunity costs of inefficient fuel use, which may be similar to coal price shocks as investigated by Linn et al. (2014). Seifert et al. (2016) find potential for technical efficiency improvements for power plants in Germany. It has been pointed out that the electricity sector incurred windfall profits due to cost pass-through and free allocation (Sijm et al., 2006). Indeed, Chan et al. (2013) find an increase in revenues during 2005 to 2009 after the introduction of the EU ETS. These financial gains may themselves have an effect on investment decisions (Pahle et al., 2011). However, case studies on the investment behaviour within the German power sector suggest that the influence of the EU ETS may be limited to small-scale investments (e.g. Hoffmann, 2007; Rogge et al., 2011). Löfgren et al. (2013) do not find evidence for an impact of the EU ETS on firm investments in manufacturing and the energy sector in Sweden.

3. Empirical Model

3.1. Input Demand Functions in Power Generation

Productivity and efficiency in the power generation sector has received attention in the economic literature before. When it comes to methodology, different approaches exist in the literature. These differ in particular concerning short-run substitution possibilities between fuel use and other input factors, such as capital and labour. On the one hand, this substitution can be included by using a "flexible" functional form for the production function (e.g. Knittel, 2002). On the other hand, Fabrizio et al. (2007) and Gao and Van Biesebroeck (2014) bring forward the idea of a Leontief production function, assuming no substitution between fuel use and other input factors in the short run. They argue that this is a suitable representation of the relationship between physical inputs and outputs in electricity generation. Electricity cannot be stored economically to a large extent, hence supply and demand have to meet at every point in time. This means that a plant's actual production might not always match its potential generation capacity, but depends on the level of residual demand for the respective power plant. Residual demand for the individual plant is determined by overall demand realizations and the structure of the merit-order at each point in time. Fuel input depends on actual generation decisions, whereas labour and capital are pre-determined and adjusted to so-called planned or probable output. This approach abstracts from the question whether competitive or non-competitive behaviour prevails but relies on the assumption of cost minimization, which should be independent of the (non-)price-taking behaviour in a "non-regulated" environment (see e.g. Borenstein, 2000).

Given these arguments, I follow the approach of Fabrizio et al. (2007) and Gao and Van Biesebroeck (2014) and assume a Leontief production function in electricity generation:

$$Q^A = min\left[Q^P\left(K, L\right)\, exp\left(\omega^A\right),\ F\left(E, \varphi\right)\right], \tag{1}$$

where Q^A is actual and Q^P is planned or probable output, which is a function of labour input L and capital input K.[14] The difference between planned and actual output is determined by a utilization shock ω^A. In the second expression, actual output is determined by fuel input E and an individual- and time-specific term φ, which captures for instance differences across plant technologies or changes in technology over time. Integrating φ explicitly in the model is a deviation from the function specified in Fabrizio et al. (2007) and Gao and Van Biesebroeck (2014) to illustrate a potential margin for differences in fuel input across time and plants.

[14]Subscripts for plants and years are dropped for notational convenience within this subsection.

Plants minimize cost to produce probable output Q^P by choosing labour L and capital input K subject to a CES production function as in Gao and Van Biesebroeck (2014), as well as acknowledging price of capital R and wage W:

$$\begin{aligned} &\underset{K,L}{\text{Min}}\; R\,K + W\,L \\ &\text{s.t. } Q^P \leq \left(\alpha\, K^{\rho} + (1-\alpha)\, L^{\rho}\right)^{\frac{\nu}{\rho}} \end{aligned} \tag{2}$$

Including capital input K and excluding non-fuel expenses as choice variables in the cost minimization framework are other deviations from Fabrizio et al. (2007) and Gao and Van Biesebroeck (2014). Whereas the first allows to investigate potentially the role of investments, the impact on non-fuel expenses cannot be analysed as this data is not available.

Solving this problem leads to the following first order condition for labour input:

$$W = (1-\alpha)\,\nu\,\lambda\; {Q^P}^{\frac{\nu-\rho}{\nu}}\; L^{\rho-1}, \tag{3}$$

where λ is the Lagrange multiplier, ν is a parameter related to returns to scale and $1/(1-\rho)$ is the elasticity of substitution. As actual output equals planned output times the utilization shock, rearranging, substituting probable with actual output, and taking the natural logarithm, leads to the following labour input demand function:

$$l = \beta_0 + \beta_q\, q + \beta_k\, k + \beta_w\, w + \upsilon^l, \tag{4}$$

where $\beta_q = (\nu-\rho)/(\nu\,(1-\rho))$, $\beta_w = -1/(1-\rho)$ and υ^l is a residual capturing, among other things, idiosyncratic productivity effects and individual utilization shocks.

As $Q^P\,(K,L)\; exp\left(\omega^A\right) \;=\; F\,(E,\varphi)$ holds in the optimum, for the derivation of the fuel input demand function, the second part of Equation 1 can be inverted and assuming a log-linear relationship written in natural logarithms as:

$$\begin{aligned} e &= F^{-1}\left(q^A, \varphi\right) \\ &= \alpha_0 + \alpha_q\, q + \upsilon^e, \end{aligned} \tag{5}$$

with υ^e being the residual of the fuel input demand function, analogously to the labour input demand function. Furthermore, φ is also subsumed in this residual term.

3.2. ETS Intensity and Input Demand

This framework is used to evaluate the impact of the EU ETS on fuel efficiency of fossil fuel power plants in Germany, i.e. the effect on fuel input given generation output under cost minimization. Furthermore, this framework also allows me to investigate potential effects on labour efficiency. Almost all fossil fuel power plants in Germany are subject to the EU ETS and face the same European-wide carbon price.[15] This prevents a clear distinction between treated and untreated power plants before and after the introduction of the EU ETS. Despite this fact, the actual exposure to the EU ETS differs by plant. Thus, I make use of differences in treatment intensity to identify the effect of the EU ETS on fossil fuel power plants. Assignment of these intensities are, however, not random but dependent on the plant's emission factor, the individual heat rate and the price of emission allowances. This highlights that not only cross-sectional differences between plants exist, but also that intensities may vary over time due to changes in carbon prices and individual heat rates. ETS intensity is thereby defined as:

$$TI_{it} = P_{CO2,t} \times \eta_{it} \times \sigma_{k\,|\,k \ni i}, \tag{6}$$

where TI_{it} is the treatment or ETS intensity of plant i in period t, $P_{CO2,t}$ is the price of emission allowances in period t in Euro per ton CO_2, η_{it} is the heat rate of plant i in period t in MWh thermal per MWh electric and σ_k is the emission factor of plant i in ton CO_2 per MWh thermal, varying with fuel type k. Thus, the ETS intensity is expressed in Euro per MWh electricity and heat generation, varying over plants and years.

To investigate how input efficiency changes with the introduction of the EU ETS, the input demand functions are augmented by the ETS intensity. Whereas fuel input is assumed to be a flexible input factor and as such varies with current ETS intensity, labour input is assumed to be pre-determined and adjusted with respect to probable output. Hence, expectations on ETS intensity at the time may influence probable output and hence, may matter for labour input instead of actual ETS intensity. Since expectations are not observable, I use the year-ahead forward prices in the previous year as a proxy in the empirical model.[16]

Furthermore, to capture time-constant individual differences across plants as well as changes over time in general market conditions (such as the rising share of renewable electricity and changes in demand levels), I include individual and time fixed effects.

The EUA price may provide similar incentives as fuel price changes (see e.g. Linn et al., 2014, for an example for coal prices). Thus, one might be worried that some potential fuel efficiency improvements are actually due to changes in fuel prices and might be falsely attributed to the introduction of the EU ETS. However, variation in fuel prices may be less pronounced than the change in marginal cost by introduction of the EU ETS. Nonetheless, to address these concerns, I include a measure of effective fuel prices (FP) similar to the ETS intensity by multiplying heat rates by the respective fuel prices for natural gas, hard coal and lignite in the fuel input demand equation.

[15] I do not observe which power plants are subject to EU ETS regulation since data on rated thermal input is not available. The results are robust to a sample with a minimum capacity of 20 MW electric. This should exclude all power plants that do not participate in the EU ETS.

[16] For the first year of the EU ETS, I have to make use of actual intensity as forward prices are not available. Results are rather insensitive to using the same intensity measure as for the fuel input equation.

Thus, the empirical model to be estimated for fuel e and labour l input demand, respectively, becomes:

$$e_{it} = \alpha_0 + \alpha_q\, q_{it} + \alpha_{ETS}\, TI_{it} + \alpha_{FP}\, FP_{it} + \mu_i + \mu_t + \epsilon_{it}, \tag{7}$$

$$l_{it} = \beta_0 + \beta_q\, q_{it} + \beta_k\, k_{it} + \beta_w\, w_{it} + \beta_{ETS}\, E_{t-1}(TI_t) + \nu_i + \nu_t + \zeta_{it}. \tag{8}$$

The main parameters of interest are α_{ETS} and β_{ETS}. An increase in carbon cost of one Euro per MWh electricity and heat generation leads to a change in input demand by ($\alpha_{ETS} * 100$) percent and ($\beta_{ETS} * 100$) percent, respectively, holding the level of output fixed. The assumption underlying this approach is that the EU ETS's impact is additive in the log-linear relationship and thus, leads to a shift in the underlying technology, i.e. the relationship between fuel input and electricity and heat output. Although this structure is the same as in Fabrizio et al. (2007) and Gao and Van Biesebroeck (2014), the "implicit null hypothesis" (Fabrizio et al., 2007) is different: Whereas the efficiency effects found in these studies stem from deviations from cost minimization behaviour before deregulation, in this study, it is a change in the underlying technology, e.g. resulting from changes in utilization, actual investments in technology, or other measures to improve fuel efficiency in response to the EU ETS.

3.3. Identification Challenges and Empirical Strategy

To obtain valid estimates of the parameters for the EU ETS effect on fuel use (α_{ETS}) and labour input (β_{ETS}), several challenges must be addressed. Due to simultaneous choice of inputs and outputs, it has been pointed out that the parameter estimates in a production function suffer from a simultaneity bias preventing identification (e.g. Marschak and Andrews, 1944; Griliches and Mairesse, 1995). One reason could be idiosyncratic productivity shocks that may influence input and output choice, but are in general unobserved by the econometrican (e.g. Olley and Pakes, 1996). These issues must also be confronted in an input demand function approach (Fabrizio et al., 2007; Gao and Van Biesebroeck, 2014). Neglecting this simultaneity bias would lead to inconsistent estimates of the respective parameters for output (α_q and β_q).

Furthermore, the assignment of different intensities is not random but depends on carbon prices, emission factors, and individual heat rates. Whereas carbon prices and emission factors may be exogenous to the individual plant[17], its heat rate is likely to be endogenous as the underlying technology is (at least in the long run) a choice variable and can be influenced by investment decisions. A price on carbon emissions represents a cost shock to the individual plant that may have a similar impact as a shock in fuel prices. For coal power plants, Linn et al. (2014) show a positive relationship between the individual heat rate and the coal price. Thus, carbon pricing may provide incentives to invest in heat rates. A further caveat stems from the fact that I do

[17]The latter may only be reasonable if there is no switching of the main fuel type. The number of reporting plants within main fuel types is quite stable over time, which lends credibility to this assumption.

not observe maximum potential heat rates but only actual measured heat rates. Thus, a further important issue is the simultaneous determination of utilization and the observable heat rate. The introduction of the EU ETS and a positive carbon price might affect the plant's place in the merit-order and hence, its utilization which in turn has consequences for its actual attainable heat rate.

I make use of two empirical strategies to confront these challenges and provide robust estimates of the effect of the EU ETS. First, the potential endogeneity of output is addressed by an instrumental variable approach following Fabrizio et al. (2007) and Gao and Van Biesebroeck (2014). As instrumental variables for output, Fabrizio et al. (2007) use state-level electricity consumption and Gao and Van Biesebroeck (2014) use province-level value added and employment in their markets under study (the United States and China, respectively). Given the structure of the German electricity market, using regional variation is not sufficient for identification.[18] Therefore, I focus on instruments that hint at the plant's position in the merit-order. The instrumental variables should explain the level of individual output but may not be correlated with idiosyncratic productivity shocks. Therefore, potential instruments for output include twice lagged individual output and output of other plants (competitors), who have a higher capacity factor.[19]

Competitor's output may be potentially endogenous if defined as total output of all plants minus production of this plant. In this case, output of plants with higher marginal cost would be included in this measure, although those plant's are likely to be affected by idiosyncratic productivity shocks of the respective plant. However, if only the output of competitors with a higher capacity factor is included, this variable may approximate the position in the merit-order and creates additional variation across plants due to different capacity factors. In addition to that, it has been pointed out that lagged individual values could be potential instruments in the context of production function estimation (e.g. Aguirregabiria, 2009; Alonso-Borrego, 2010). This approach rests on the implicit assumption of no serial correlation of productivity shocks. Transferring this assumption to the input demand framework, lagged individual output might not be correlated with idiosyncratic productivity shocks in the current year, but may hint at the plant's general place in the merit-order and thus, have explanatory power for current output.

Second, in order to tackle the potential endogeneity of individual heat rates in the ETS intensity as well as in the effective fuel price variable, I construct a measure of ex-ante exposure that relies on average actual achieved heat rates before the introduction of the EU ETS. Thus, ETS Ex-Ante

[18] Federal state level value added, gross domestic product and electricity consumption do not have enough explanatory power to be used as an instrumental variable.

[19] Capacity factors are defined as the ratio of electricity generated by the plant to its generation potential, indicating the plant's utilization.

Exposure (EAE) is defined as the product of the carbon price in period t, emission factor of fuel type k and the average heat rate in 2003 and 2004 for plant i:

$$EAE_{it} = P_t \times \overline{\eta}_{i,2003-2004} \times \sigma_{k\,|\,k\ni i}.$$

For Fuel Price Ex-Ante Exposure ($FP\ EAE$) average individual heat rates in 2003 and 2004 are multiplied by the respective fuel price. This approach is similar to the approach by Mian and Sufi (2012) who also investigate a program that potentially affects the entire population (Cash for Clunkers) and make use of different ex-ante intensities. The underlying assumption of this approach is that plants do not adjust heat rates before the introduction of the EU ETS in response to its announcement. The EU ETS Directive in October 2003 stated that EU Member States decide on individual initial plant allocation of emission certificates. The German government decided in March 2004 on its National Allocation Plan (NAP), opting for grandfathered emission certificates based on individual emissions from 2000 to 2002 for the first trading phase from 2005 to 2007. Within the NAP, the total amount of emission certificates to be allocated free of charge for the second trading phase starting in 2008 was already determined. However, it neither defined whether the certificates would be grandfathered again nor which specific period would be used to set allocations. In 2006, it was decided to use historical emissions from 2000 to 2005. One concern could be that free allocation of emission certificates based on historical emissions could provide incentives to plant owners to increase emissions before the introduction of the EU ETS in order to increase the amount of grandfathered emission certificates. As electricity cannot be economically stored to a large amount and supply and demand has to match at each point in time, anticipatory effects could be expected to affect investments in heat rate improvements. As detailed heat rate investment data is not available, individual plant investment in machinery in 2003 and 2004 is used as a proxy. To observe investment behaviour before 2003, I make use of data on aggregated investments in machinery in the German electricity generation sector from Destatis (2016). This data is available for the Federal Republic of Germany from 1992 on.[20] However, compared to the sample of fossil fuel power plants at hand, the figures relate to the total electricity generation sector including also non-fossil fuel power plants.

[20]Statistics that date back to the 1970's are only available for the old West German states.

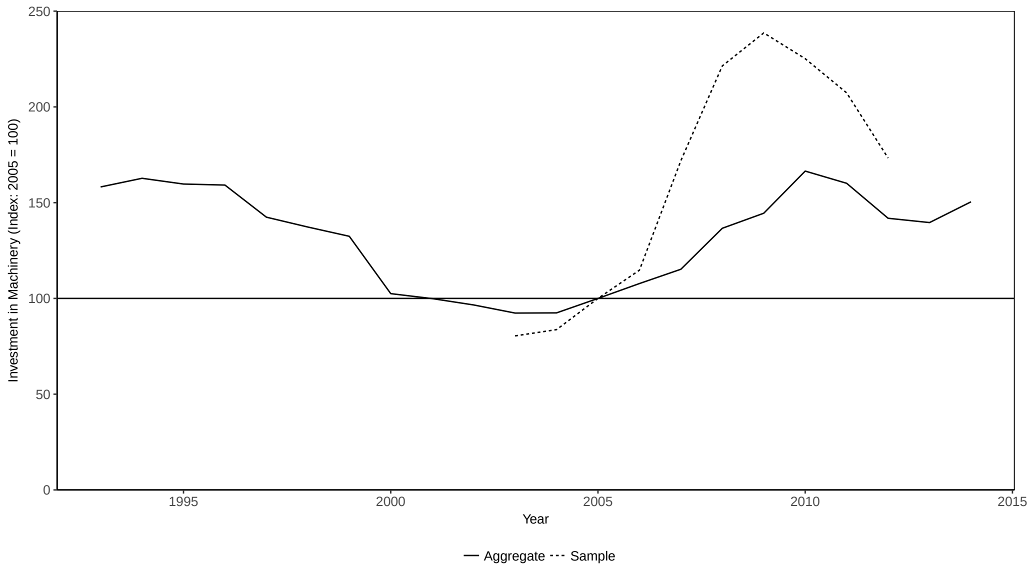

Figure 2: Investment in Machinery - Energy and Water Industry and Within Sample

Notes: The solid line represents the annual values of the index of investment in machinery (2005 = 100) within the total electricity generation sector from 1993 until 2014. The index is calculated based on data from Destatis (2016). The dashed line shows the respective index for fossil fuel power plants in the sample and is calculated based on data from Research Data Centre of the Statistical Offices Germany (2016).

In Figure 2, the annual investment in machinery in the sample varies more than annual aggregate investment, but the direction of changes is approximately similar. In the aggregate data, there is a reduction in investment until 2005, with a comparably rather stable period from 2000 until 2004. From 2005 on, investments in machinery increases. These aggregate figures are only indicative as they might not solely be related to the introduction of the EU ETS, but may be driven by other factors as well. For instance, Germany liberalized its electricity market in 1998. Before 1998, power plants were subject to cost-plus regulation, which may have incentivized a high investment level. This may be one explanation for the reduction in annual investment after this date. Overall, the aggregate figures do not indicate large changes in investment behaviour in 2003 and 2004 compared to the previous years, and thus, do not lend support to anticipatory effects in investments.

4. Data

The administrative annual plant-level data on nearly all fossil fuel power plants in Germany from 2003 to 2012 is derived from three different data sets provided by the German Statistical Offices (Research Data Centre of the Statistical Offices Germany, 2016). The first two are combined in the annual AFiD Panel Energy Plants and provide information on employment and investment of energy plants. The third data set used is the monthly report on electricity generating plants with a capacity of more than one MW, providing information on capacity, (main) fuel type, electricity and heat generation as well as fuel input. I only consider plants with their main activity being the production of electricity as indicated by the respective NACE code.[21] Furthermore, I restrict the sample to fossil fuel power plants, i.e. plants with hard coal, lignite or natural gas as their main fuel type. The data encompasses on average about 85 percent of fossil fuel electricity generation in Germany. Labour input is defined as the annual sum of hours worked and wages as the average labour cost per hour. Capital is approximated by available capacity of the plant in MW. I observe inputs and outputs in physical units in the generation of electricity and heat. Thus, I can take into account potential differences in qualities, especially in the energy content of the fuel used. Capacity factor is calculated as the ratio of net electricity generation to available capacity multiplied by the number of possible running hours.

The descriptive statistics offered in Table 1, Table 2 and Table 3 illustrate remarkable variation across observations. Looking at statistics divided by fuel types suggests that a large part of this variation originates from differences across the different fuel types. Hard coal and lignite power plants are in general larger and invest more in machinery than natural gas power plants. As lignite plants are supposed to be baseload plants, i.e. power plants that provide continuous supply over the year, they are expected to have the highest capacity factor compared to hard coal and natural gas. This is also reflected in the descriptive statistics. While hard coal and natural gas have comparable average capacity factors, the variation within natural gas plants appears to be higher. This may reflect the larger heterogeneity of technology used by natural gas plants, ranging from rather simple gas turbines to combined-cycle plants.

[21]NACE is the "Statistical Classification of Economic Activities in the European Community" and similar to the SIC ("Standard Industrial Classification").

2003

Variable	**N**	**Mean**	**S.D.**	**p10**	**p25**	**p50**	**p75**	**p90**
Total								
Capacity (MW)	302	184.40	420.14	0.32	1.41	10.81	162.00	564.00
Labour (hours)	95	36,258.04	71,530.87	4,296.17	7,306.33	15,022.42	33,890.75	82,366.00
Fuel use (GJ)	302	870,854.92	2,428,282.50	1,627.67	6,081.67	54,837.04	615,411.00	2,217,797.10
Generation (MWh)	302	104,734.08	243,069.98	289.51	1,294.17	9,104.88	99,694.83	287,949.75
Investment Machinery (EUR)	119	4,438,072.10	9,181,449.40	69,030.00	721,744.00	1,841,129.00	4,497,496.00	12,001,078.00
Capacity Factor	301	0.51	0.34	0.17	0.33	0.50	0.65	0.78
Ex-Ante Exposure (EUR/MWh)	318	0.00	0.00	0.00	0.00	0.00	0.00	0.00
- Only Hard Coal Power Plants								
Capacity (MW)	63	362.99	337.68	64.00	86.00	281.00	599.00	720.00
Labour (hours)	24	69,697.70	121,197.34	–[a]	17,810.88	26,751.96	64,424.96	–[a]
Fuel use (GJ)	63	1,665,744.30	1,506,800.80	268,894.08	556,595.42	1,345,180.50	2,554,185.70	3,379,462.50
Generation (MWh)	63	205,878.42	162,506.60	43,901.17	73,066.50	176,614.50	305,298.25	377,504.75
Investment Machinery (EUR)	24	9,348,755.00	17,412,229.00	–[a]	966,372.00	2,568,393.50	12,236,713.00	–[a]
Capacity Factor	62	0.56	0.21	0.34	0.43	0.56	0.66	0.75
Ex-Ante Exposure (EUR/MWh)	64	0.00	0.00	0.00	0.00	0.00	0.00	0.00
- Only Lignite Power Plants								
Capacity (MW)	25	788.90	1,048.79	–[a]	33.50	151.00	1,585.00	–[a]
Labour (hours)	12	64,327.51	59,035.85	–[a]	11,199.58	47,726.12	111,460.33	–[a]
Fuel use (GJ)	25	5,031,284.10	6,536,988.20	–[a]	184,733.56	1,345,413.30	9,216,955.20	–[a]
Generation (MWh)	25	512,160.90	618,865.46	–[a]	26,221.25	167,679.92	1,102,554.60	–[a]
Investment Machinery (EUR)	17	4,824,437.70	6,318,219.50	–[a]	1,116,222.00	3,379,536.00	5,693,199.00	–[a]
Capacity Factor	25	0.67	0.25	–[a]	0.53	0.77	0.85	–[a]
Ex-Ante Exposure (EUR/MWh)	25	0.00	0.00	–[a]	0.00	0.00	0.00	–[a]
- Only Natural Gas Power Plants								
Capacity (MW)	214	61.20	157.28	0.20	0.97	3.15	26.00	206.00
Labour (hours)	59	16,946.42	28,312.14	2,882.50	6,090.75	9,297.42	17,781.42	34,560.67
Fuel use (GJ)	214	150,813.98	342,843.17	1,064.33	2,975.75	14,365.83	90,567.58	465,250.33
Generation (MWh)	214	27,361.35	64,249.54	187.70	641.83	2,816.43	19,754.90	87,762.09
Investment Machinery (EUR)	78	2,842,884.90	4,494,614.40	15,011.00	627,081.00	1,572,887.00	2,498,540.00	6,120,308.00
Capacity Factor	214	0.47	0.37	0.12	0.29	0.45	0.62	0.76
Ex-Ante Exposure (EUR/MWh)	229	0.00	0.00	0.00	0.00	0.00	0.00	0.00

a Values cannot be displayed due to confidentiality issues.

Table 1: Summary Statistics - Overall and Differentiated by Fuel Type in 2003

2008

Variable	**N**	**Mean**	**S.D.**	**p10**	**p25**	**p50**	**p75**	**p90**
Total								
Capacity (MW)	319	180.64	416.71	0.50	1.48	9.78	160.00	588.00
Labour (hours)	117	27,948.65	50,625.27	3,475.25	6,641.25	12,628.33	30,103.92	67,695.00
Fuel use (GJ)	319	783,544.24	2,276,184.30	2,254.00	7,317.33	37,352.17	500,656.68	1,858,684.80
Generation (MWh)	319	94,484.97	230,667.57	488.49	1,570.01	7,649.02	82,878.67	264,339.25
Investment Machinery (EUR)	193	7,945,467.40	38,988,220.00	0.00	20,690.00	572,376.00	2,740,192.00	9,265,957.00
Capacity Factor	319	0.60	0.77	0.18	0.34	0.50	0.67	0.83
Ex-Ante Exposure (EUR/MWh)	255	9.39	5.39	5.17	5.56	6.36	11.71	18.99
- Only Hard Coal Power Plants								
Capacity (MW)	60	381.52	327.04	64.80	121.85	292.50	624.99	744.50
Labour (hours)	29	50,698.09	84,369.07	$-^a$	16,296.58	22,148.58	42,651.00	$-^a$
Fuel use (GJ)	60	1,541,409.70	1,358,710.20	275,291.80	482,984.42	1,225,356.50	2,361,021.70	3,165,604.30
Generation (MWh)	60	187,521.70	149,530.81	39,658.88	82,961.91	155,135.29	264,993.63	358,855.04
Investment Machinery (EUR)	43	11,903,911.00	37,644,157.00	52,508.00	234,000.00	1,523,775.00	7,806,793.00	25,036,000.00
Capacity Factor	60	0.50	0.13	0.34	0.42	0.50	0.59	0.66
Ex-Ante Exposur (EUR/MWh)	53	15.16	4.05	9.33	11.02	15.87	18.98	19.76
- Only Lignite Power Plants								
Capacity (MW)	21	973.26	1,092.56	$-^a$	67.00	732.73	1,787.00	$-^a$
Labour (hours)	14	52,747.71	51,200.44	$-^a$	10,135.08	31,676.92	86,349.67	$-^a$
Fuel use (GJ)	21	5,796,111.60	6,520,650.40	$-^a$	684,657.92	2,202,092.10	11,331,562.00	$-^a$
Generation (MWh)	21	591,987.18	623,915.56	$-^a$	60,450.73	253,646.25	1,175,961.10	$-^a$
Investment Machinery (EUR)	13	59,595,672.00	125,900,000.00	$-^a$	1,301,347.00	1,837,312.00	27,276,994.00	$-^a$
Capacity Factor	21	0.68	0.21	$-^a$	0.47	0.77	0.83	$-^a$
Ex-Ante Exposure (EUR/MWh)	20	19.54	5.04	$-^a$	17.76	20.00	23.31	$-^a$
- Only Natural Gas Power Plants								
Capacity (MW)	238	60.06	158.59	0.22	1.08	3.18	23.10	178.00
Labour (hours)	74	14,341.62	19,085.83	2,963.33	5,405.33	8,088.38	16,243.75	33,075.00
Fuel use (GJ)	238	150,200.36	359,875.40	1,632.17	5,454.08	14,351.70	90,147.83	424,056.33
Generation (MWh)	238	27,133.08	65,561.86	339.00	1,087.50	2,938.58	18,750.75	79,993.20
Investment Machinery (EUR)	137	1,801,921.80	3,298,937.10	0.00	0.00	370,880.00	1,857,690.00	5,661,971.00
Capacity Factor	238	0.62	0.89	0.16	0.30	0.49	0.67	0.85
Ex-Ante Exposure (EUR/MWh)	182	6.59	2.10	5.08	5.37	5.83	6.82	9.67

a Values cannot be displayed due to confidentiality issues.

Table 2: Summary Statistics - Overall and Differentiated by Fuel Type in 2008

2012

Variable	N	Mean	S.D.	p10	p25	p50	p75	p90
Total								
Capacity (MW)	300	218.95	495.55	0.38	1.42	12.95	227.50	683.00
Labour (hours)	106	26,819.04	39,793.99	2,974.50	6,705.67	12,085.04	23,613.08	80,713.25
Fuel use (GJ)	300	824,976.91	2,526,292.30	1,547.43	6,756.71	46,133.24	565,553.83	1,915,334.60
Generation (MWh)	300	99,590.01	258,932.28	335.29	1,401.21	8,312.75	93,976.92	266,181.34
Investment Machinery (EUR)	153	8,393,778.90	27,095,021.00	0.00	135,383.00	992,054.00	4,661,127.00	14,733,845.00
Capacity Factor	300	0.46	0.25	0.12	0.27	0.48	0.65	0.78
Ex-Ante Exposure (EUR/MWh)	215	3.11	1.77	1.67	1.81	2.14	3.91	6.16
- Only Hard Coal Power Plants								
Capacity (MW)	61	419.21	328.53	78.00	140.00	342.72	661.00	812.00
Labour (hours)	25	36,531.61	35,123.06	–[a]	14,765.92	22,222.75	40,071.58	–[a]
Fuel use (GJ)	61	1,497,811.90	1,234,944.30	251,183.38	586,045.08	1,333,275.20	2,124,386.00	2,788,752.00
Generation (MWh)	61	180,805.23	137,137.19	43,667.83	82,594.58	144,117.75	258,738.83	325,759.75
Investment Machinery (EUR)	40	13,174,306.00	40,000,064.00	118,926.00	298,141.00	1,025,623.50	4,420,578.00	30,117,952.00
Capacity Factor	61	0.46	0.15	0.27	0.35	0.48	0.56	0.64
Ex-Ante Exposure (EUR/MWh)	50	4.98	1.25	3.19	3.76	5.22	6.10	6.37
- Only Lignite Power Plants								
Capacity (MW)	17	1,267.65	1,336.75	–[a]	164.00	875.00	1,947.25	–[a]
Labour (hours)	10	69,912.66	46,068.75	–[a]	27,977.50	65,524.17	114,471.17	–[a]
Fuel use (GJ)	17	7,298,562.00	7,698,205.00	–[a]	1,264,260.50	4,690,982.90	11,773,368.00	–[a]
Generation (MWh)	17	755,217.11	756,285.26	–[a]	157,373.17	521,879.08	1,238,296.40	–[a]
Investment Machinery (EUR)	14	21,713,697.00	47,812,867.00	–[a]	314,229.00	1,196,638.50	13,256,311.00	–[a]
Capacity Factor	17	0.66	0.18	–[a]	0.55	0.67	0.77	–[a]
Ex-Ante Exposure (EUR/MWh)	15	6.44	1.75	–[a]	5.95	6.44	7.89	–[a]
- Only Natural Gas Power Plants								
Capacity (MW)	222	83.62	243.95	0.120	1.17	4.29	39.80	211.00
Labour (hours)	71	17,329.60	35,905.32	2,814.500	5,397.67	8,762.25	14,924.50	34,416.67
Fuel use (GJ)	222	144,373.83	340,922.87	655.333	4,528.17	13,156.42	87,648.06	388,832.12
Generation (MWh)	222	27,068.43	63,442.97	111.611	807.88	2,427.30	16,109.82	83,466.08
Investment Machinery (EUR)	99	4,578,627.90	12,218,751.00	0.000	30,047.00	992,054.00	4,049,328.00	11,325,268.00
Capacity Factor	222	0.45	0.27	0.093	0.23	0.45	0.65	0.79
Ex-Ante Exposure (EUR/MWh)	150	2.15	0.70	1.647	1.75	1.89	2.22	3.16

a Values cannot be displayed due to confidentiality issues.

Table 3: Summary Statistics - Overall and Differentiated by Fuel Type in 2012

One drawback of this dataset is that only the main fuel type of the plant is observed, although plants may consist of several generating units. In the following, I treat plants according to their main fuel type under the assumption that the main fuel type has the determining influence on the plant's decisions. An additional challenge arises through the matching of different data sets, i.e. the AFiD Panel Energy Plants and the monthly report on electricity generating plants. The varying coverage of these data sets results in a large number of missing values for labour input. This problem is not as severe in the fuel input demand equation since all variables for this equation are part of the same survey. To overcome concerns that different findings for fuel and labour are driven by differences in the two samples, I first checked to which extent the two samples are comparable. The sample with information on labour input represents 60 percent of electricity production of the full sample. It also differs along other dimensions. Plants with information on labour input are on average larger (capacity as well as electricity and heat generation) and have a higher ETS

Ex-Ante Exposure. Average heat rates are, however, rather similar compared to the full sample. Given these differences, I re-estimate as a robustness check the fuel input demand equation only for plants that are reporting in both data sets. In addition to that, it appears that there are some inconsistencies in the reported values as some heat rates would imply efficiency rates (the inverse of the heat rate) larger than 100 percent. This would violate the law of conservation of energy in physics as this would imply more energy after the conversion of fuel into electricity. In order to address this issue, I trim the data set based on heat rate values by the lower and upper 2.5 percent in the reference specification.[22]

Furthermore, I complement the data set with information on the year of commissioning, stemming from the German Federal Network Agency (BNetzA, 2014). As plants can consist of various generating units, there can be different years of commissioning of units within one plant. I have added the oldest, youngest, and a capacity-weighted average commissioning year to the data set as a proxy for the plant's vintage. The data from the Federal Network Agency encompasses all power plants with a net capacity of larger than or equal to 10 MW. This means that especially smaller power plants cannot be assigned a year of commissioning. The matching is done by the statistical offices based on municipality codes, fuel types, and net capacity of the plants.

ETS Ex-Ante Exposure is calculated as indicated in Equation 3.3, using the volume-weighted annual average of day-ahead daily settlement EUA prices calculated with data from the EEX, emission factors based on the plant's main fuel type from UBA (2013) as well as calculated actual achieved heat rates based on fuel input and plant output in 2003 and 2004 from Research Data Centre of the Statistical Offices Germany (2016). In the case of the Fuel Price Ex-Ante Exposure for hard coal, natural gas and lignite, I use the respective individual average heat rates of plants in 2003 and 2004 and multiply these values by the respective fuel price. For natural gas, I take the volume-weighted annual cross border price for Germany provided by BAFA (2015b). The annual fuel price for hard coal stems from BAFA (2015a). Given that there is no trade in lignite, I assume constant fuel prices for lignite of 0,4 Euro per GJ following BMWi (2014).

[22] As a robustness check, I also use (a) the whole data set, (b) trimmed by the lower and upper 0.5 percent as well as (c) dropping all observations with efficiency rates larger than 100 percent. All these robustness checks lead to results that are consistent with the results in the reference specification.

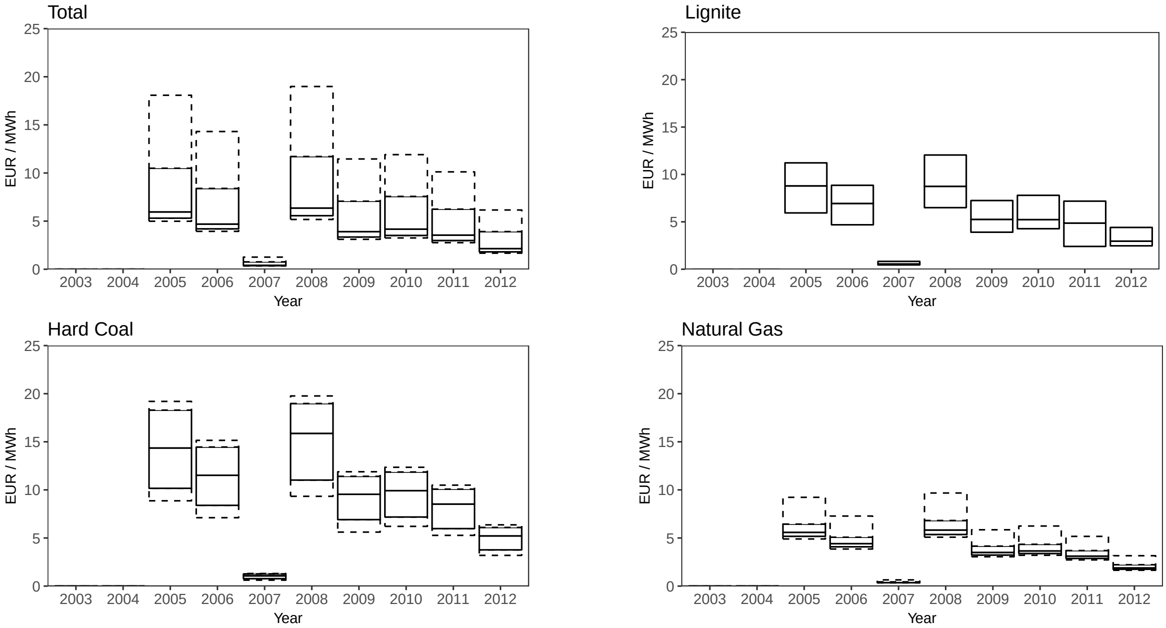

Figure 3: Distribution of Annual ETS Ex-Ante Exposure

Notes: This figure consists of four panels showing the distribution of annual ETS Ex-Ante Exposure divided into total (all technologies pooled) and by main fuel type (hard coal, lignite and natural gas). Each box plot displays the 10th percentile (bottom dashed line), first quartile (lower solid line), the median (middle solid line), the third quartile (upper solid line) and the 90th percentile (top dashed line). The 10th and 90th percentile for annual Ex-Ante Exposure of lignite power plants cannot be displayed due to confidentiality issues. Own calculation based on data from the Research Data Centre of the Statistical Offices Germany (2016).

The lower solid line of the box in Figure 3 shows the first quartile of the ETS Ex-Ante Exposure, whereas the middle solid line depicts the median and the upper solid line the third quartile. The bottom dashed line depicts the 10th percentile, whereas the upper dashed line shows the 90th percentile.[23] The exposure measured in Euro per MWh electricity and heat generation varies substantially over time, which is due to changes in emission certificate prices. Dividing the ETS Ex-Ante Exposure by fuel type illustrates that the overall within year variation is not exclusively due to differences in emission intensity of fuels, but also that the exposure varies across plants of the same fuel type within a given year. This exemplifies the importance of differences in heat rates of individual plants for the ex-ante exposure of plants to the EU ETS. In the empirical model, the identification of the effect of the EU ETS on within plant variation in input demand derives mainly from within fuel type variation in ETS Ex-Ante Exposure.

The within fuel type variation comes from two sources: changes in the EUA price over time and variation in average actual measured heat rates in 2003 and 2004 across plants with the same main fuel type. First, the EUA price varies over time ranging from more than 20 to less than 10 Euro

[23] Due to confidentiality issues, the minimum and maximum cannot be shown. Furthermore, the 10th and 90th percentile for Ex-Ante Exposure of lignite power plants cannot be displayed.

per ton CO_2 as can be seen in Figure 4. In general, spot (day-ahead) and forward market prices evolve in a similar fashion. The largest difference appears in 2007. The low spot price indicates the lack of shortages of emission certificates at the end of the first trading period in 2007 as banking of emission permits from Phase I to Phase II was not allowed.

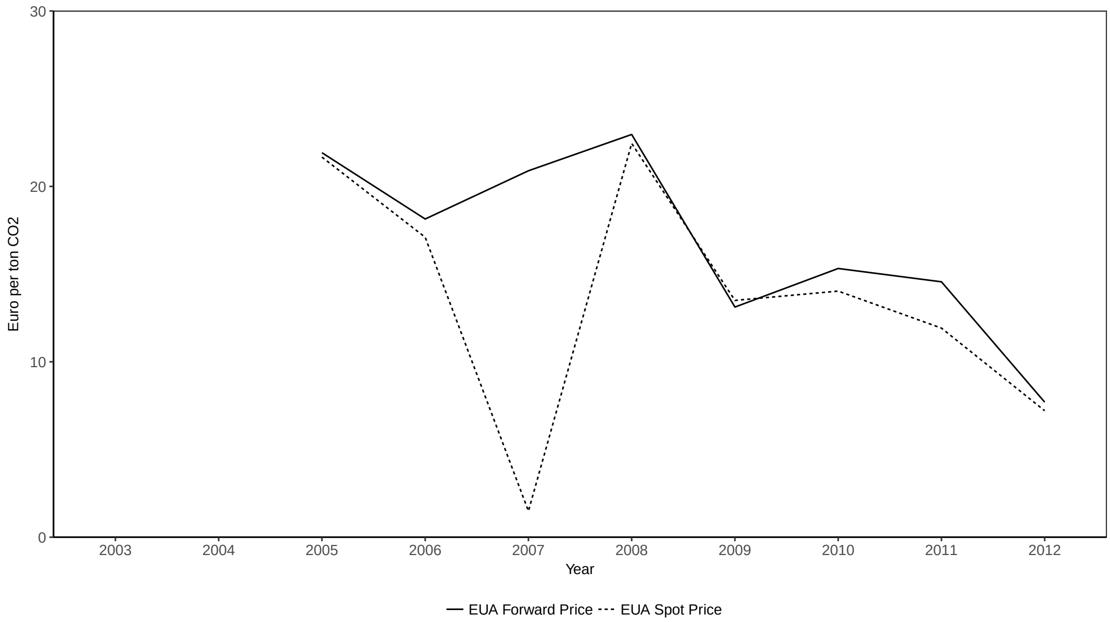

Figure 4: Development of EUA Spot and Forward Prices

Notes: The dashed line depicts the volume-weighted annual average of day-ahead (spot) daily settlement EUA prices in Euro per ton CO_2. The solid line shows the volume-weighted annual average of forward prices. Calculations are based on data from the European Energy Exchange (EEX).

Second, Figure 5 depicts the distribution of average actual measured heat rates in 2003 and 2004 over the course of the sample period for all fossil fuel power plants (*Total*) and divided by main fuel type. The lower solid line depicts the first quartile, the middle solid line the median and the upper solid line the third quartile. The top dashed line illustrates the 90th percentile, while the bottom dashed line shows the 10th percentile. The figure illustrates that even within fuel types there is large variation in actual measured heat rates across power plants.

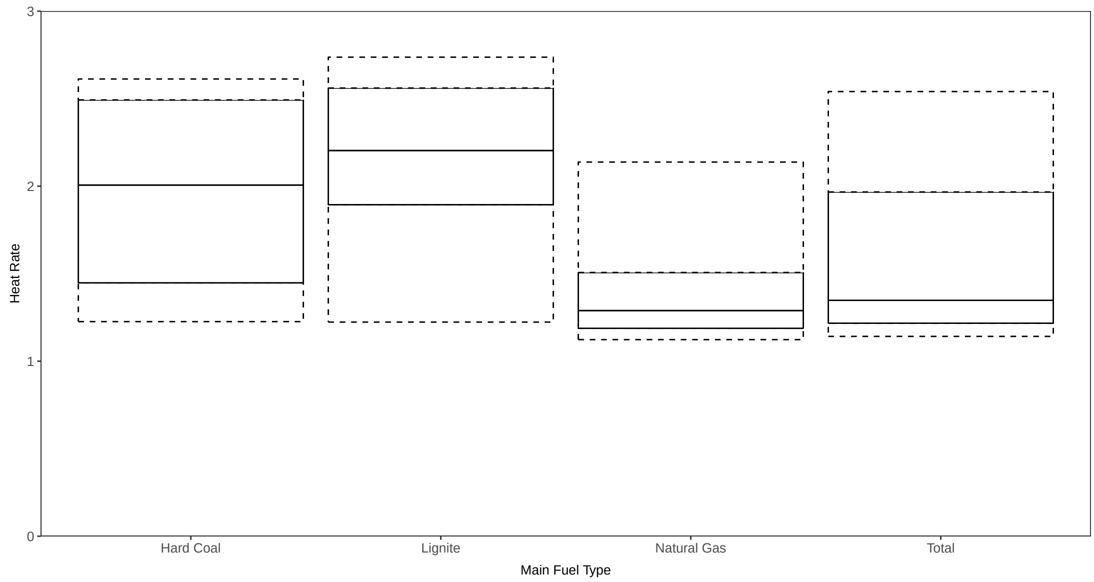

Figure 5: Distribution of Average Actual Measured Heat Rates in 2003 and 2004

Notes: This figure shows the distribution of average actual measured heat rates in 2003 and 2004 pooled over the sample period for all technologies (total) as well as for the three main fuel type categories (hard coal, lignite and natural gas). Each box plot displays the 10th percentile (bottom dashed line), first quartile (lower solid line), the median (middle solid line), the third quartile (upper solid line) and the 90th percentile (top dashed line). Own calculation based on data from Research Data Centre of the Statistical Offices Germany (2016).

5. Results

5.1. Average Effects on Fuel and Labour Efficiency

The first two columns of Table 4 depict the estimates of parameter α_{ETS} in Equation 7, whereas columns (3) and (4) present the parameter estimates of β_{ETS} in Equation 8, with ETS intensity (TI) replaced by ETS Ex-Ante Exposure (EAE) and effective fuel prices (FP) by Fuel Price Ex-Ante Exposure ($FP\ EAE$), respectively. For each dependent variable, fuel input or labour input, two different specifications are estimated. In columns (1) and (3) the twice-lagged variables of electricity and heat generation are used as instrumental variables for plant output ($L.q$). The models are estimated using forward orthogonal deviation transformations to account for individual fixed effects (Arellano and Bover, 1995). In columns (2) and (4), the output of competitors with a higher capacity factor is used as an instrument ($C.q$), and within transformations are employed to address individual fixed effects. A set of year dummy variables are included in each specification to control for time fixed effects.

The first stage F-Statistic is larger than the 10 percent Stock-Yogo critical values in the specifications with competitors' output and thus, lending support to the relevance of the instrument. The Arellano-Bond test and the Hansen test both hint at the validity of twice-lagged output as instruments for individual output.

Dependent Variable:	(1) ln(fuel)	(2) ln(fuel)	(3) ln(labour)	(4) ln(labour)
ETS Ex-Ante Exposure	-0.0042^{***}	-0.0044^{***}	0.0006	0.0016
	(0.0010)	(0.0010)	(0.0020)	(0.0019)
First Stage F-Statistic		28.53		32.48
Stock-Yogo critical values (10%)		16.38		16.38
Arellano-Bond test AR(1) p-value	0.009		0.046	
Arellano-Bond test AR(2) p-value	0.722		0.362	
Hansen test p-value	0.604		0.119	
Number of instruments	36	1	36	1
Observations	2,246	2,569	868	994
Instruments	L.q	C.q	L.q	C.q
Time Fixed Effects	+	+	+	+
Individual Fixed Effects	+	+	+	+

Notes: In this table the coefficient of the ETS Ex-Ante Exposure obtained in a regression of fuel input or labour input on ETS Ex-Ante Exposure, Fuel Price Ex-Ante Exposure, individual electricity and heat generation, year and individual fixed effects is shown. In the models of labour input in column (3) and (4), wages and available capacity (capital) are additional explanatory variables. Heat rate values are trimmed at 2.5/97.5 percent level. The first and the third columns refer to two-step difference GMM estimation using forward orthogonal deviation transformations. Standard errors are in parentheses and clustered at the plant level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 4: Average Effects - Fuel and Labour Input

The average effect in Table 4 for the effect on fuel efficiency is around -0.004. The effect is statistically significant at all conventional levels of significance. In other words, an increase in individual carbon cost of one Euro per MWh leads to a reduction in input demand by around 0.4 percent on average, holding the level of output fixed. To put this into the context of an average ETS cost of around six Euro in this sample from 2005 to 2012 and assuming a linear relationship, this translates into an increase in fuel efficiency by around 2.4 percent that can be attributed to the introduction of the EU ETS.

Concerning the labour input demand equation, none of the parameter estimates for the ETS Ex-Ante Exposure are statistically significant. Thus, there is no evidence that the introduction of the EU ETS had an impact on labour efficiency on average.

Besides average effects over all plants, the size of the effects for individual plants may vary by main fuel type, size or age. However, I find no evidence of heterogeneous effects with respect to different fuel types and age categories for neither fuel nor labour efficiency. For larger power plants, however, the fuel efficiency effects seem to be somewhat smaller.[24] This could be an indication that large power plants are maybe already quite efficient and that there are less small-scale measures for improvements left that could be implemented.

[24]The corresponding results as well as the definition of the categories can be found in the appendix.

5.2. *Robustness Checks for Average Fuel Efficiency Results*

I do various robustness checks for the fuel input demand equation to assess potential remaining concerns and challenges with the estimation strategy and the underlying data.

Dependent Variable: ln(fuel)	(1)	(2)	N
1. Forward prices	-0.0042^{***}	-0.0044^{***}	2,246 (1) / 2,569 (2)
	(0.0011)	(0.0013)	
2. Labour demand sample	-0.0034^{**}	-0.0032^{**}	882 (1) / 1,003 (2)
	(0.0009)	(0.0015)	
3. Sample until 2010	-0.0005	-0.0054^{***}	1,831 (1) / 1,920 (2)
	(0.0010)	(0.0011)	
4. Plants > 20 MW	-0.0049^{***}	-0.0044^{***}	1,143 (1) / 1,291 (2)
	(0.0013)	(0.0015)	
5. Balanced sample	-0.0022^{**}	-0.0032^{**}	1,460 (1) / 1,626 (2)
	(0.0009)	(0.0009)	
6. Single unit plants	-0.0024	-0.0013	633 (1) / 727 (2)
	(0.0024)	(0.0010)	
Explanatory Variable	Ex-Ante Exposure	Ex-Ante Exposure	
Instruments	L.q	C.q	
Time Fixed Effects	+	+	
Individual Fixed Effects	+	+	

Notes: In this table the coefficient of the ETS Ex-Ante Exposure obtained in a regression of fuel input on ETS Ex-Ante Exposure, Fuel Price Ex-Ante Exposure, individual electricity and heat generation, year and individual fixed effects is shown. Heat rate values are trimmed at 2.5/97.5 percent level. The first two columns refer to two-step difference GMM estimation using forward orthogonal deviation transformations. Standard errors are in parentheses and clustered at the plant level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 5: Average Effects - Fuel Input - Robustness Checks

First, Figure 4 hints in general to a similar evolution of spot and forward prices except for the drop in spot prices at the end of 2007, whereas the forward prices indicate that a higher price is expected for the following years. However, expected carbon prices may be relevant for deciding to improve fuel efficiency. Thus, I estimate the fuel input demand equation with an ETS Ex-Ante Exposure based on forward prices as a proxy for expectations over future carbon prices instead of spot prices, yielding nearly exact the same results.

Second, an analysis of sample differences between fuel and labour input demand equation reveals that plants used for estimating the fuel demand equation are different from plants that report labour data (as mentioned in the data section). In general, the plants reporting labour are larger in terms of capacity and generation. With regard to different fuel types, a large share of natural gas plants do not report labour information. The sample of plants with information on labour consistently display a larger ETS Ex-Ante Exposure. Although, the sample with labour information represents around 60 percent of fossil fuel electricity generation, one might be concerned that these differences in plant characteristics between the samples might be one reason for different findings across the fuel and labour demand equation. Thus, I estimate the fuel demand equation only for plants that also report labour data. The results are similar (statistically significant negative estimate for ETS Ex-Ante Exposure) but of a somewhat lower magnitude.

Third, the energy industry in general but especially in Germany is undergoing significant changes in recent years. One aspect is the increasing share of electricity generated by renewable energy technologies. These technologies may have a significant impact on the energy system as a whole but also on individual plant efficiencies due to effects on ramping needs (see e.g. Graf and Marcantonini, 2016). To investigate potential confounding effects I restrict the time period up until 2010 before the large increases in renewable capacity, especially, wind and solar PV took place. I find positive efficiency effects with a larger magnitude for the specification using competitor output as an instrument, but no effect in the specification with twice lagged individual output as instrument.

Fourth, almost all fossil fuel power plants in Germany are subject to the EU ETS. However, I cannot identify the few plants that are not regulated under the EU ETS since rated thermal input (the ETS exclusion criterion) cannot be observed in the data. Thus, I may treat some plants as being regulated even though they are not. To assess the size of this potential bias, I estimate a specification that only includes plants with an electric capacity of more than 20 MW. This threshold should be large enough to exclude any unregulated plants. The findings hold also for these "larger" plants, suggesting that the potential bias is small.

Fifth, the panel used in this analysis is unbalanced. This gives rise to a potential selection problem, if plants that are least efficient exit the market in reaction to the introduction of the EU ETS. However, given the structure of the surveys underlying the data used in this paper, plant exit is unobservable. Plants can stop reporting or do not report in one period but continue in another one due to changing reporting obligations. Especially plants around the threshold for reporting duty may report in one period but not in another without leaving the market. As a robustness check, I only use plants reporting in every time period, i.e. a balanced sample. The results remain similar, but are lower in magnitude.

Sixth, an interesting case is the differentiation between single and multi generation unit plants. Whereas the former can only improve the single generation unit to increase fuel efficiency, the latter have an additional margin: the optimization among different generating units in response to the EUA price may yield a different fuel efficiency for the overall plant. I check whether the results of an increase in fuel efficiency still holds for single unit plants as a robustness check. I find that the effects have a negative sign and are smaller in magnitude, but are not statistically significantly different from zero any longer. On the one hand, this may underline the importance of having the additional margin of internal optimization among multiple generation units. On the other hand, single generating units differ from plants with multi generating units along other dimensions as well. Plants with multiple generating units are on average larger in terms of capacity, generation and fuel input and invest more in machinery. However, the composition of power plants with respect to the main fuel type is similar for single and multiple generating unit power plants.

5.3. Investment and Utilization

To investigate possible channels through which the identified effects work, I analyse two different variables that may be affected by the introduction of the EU ETS, namely investment in machinery and utilization (expressed as the capacity factor). I again use variation in ETS Ex-Ante Exposure for identification and both equations include the Fuel Price Ex-Ante Exposure. Thus, the model that I estimate is as follows:

$$Y_{it} = \gamma_0 + \gamma_{ETS}\, EAE_{it} + \gamma_{FP}\, (FP\, EAE)_{it} + \tau_i + \tau_t + \psi_{it}, \tag{9}$$

where Y_{it} is investment in machinery or capacity factor, respectively, of plant i at time t.

Although observed investment in machinery may be more accurate to use than observed total investment, it does not only contain actual investment in generation units but also includes expenses for office and business equipment. Such expenditures may also be reflected in the investment data, which is not as lumpy as might be expected and contains positive values for almost all observations. To uncover actual investment in generation facilities, I distinguish between these different types of investment by normalizing the investment amount by the plant's individual capacity. The kernel density estimate shown in Figure 6 reveals a bimodal empirical distribution of investments in machinery normalized by the plant's capacity in MW and transformed by the natural logarithm.

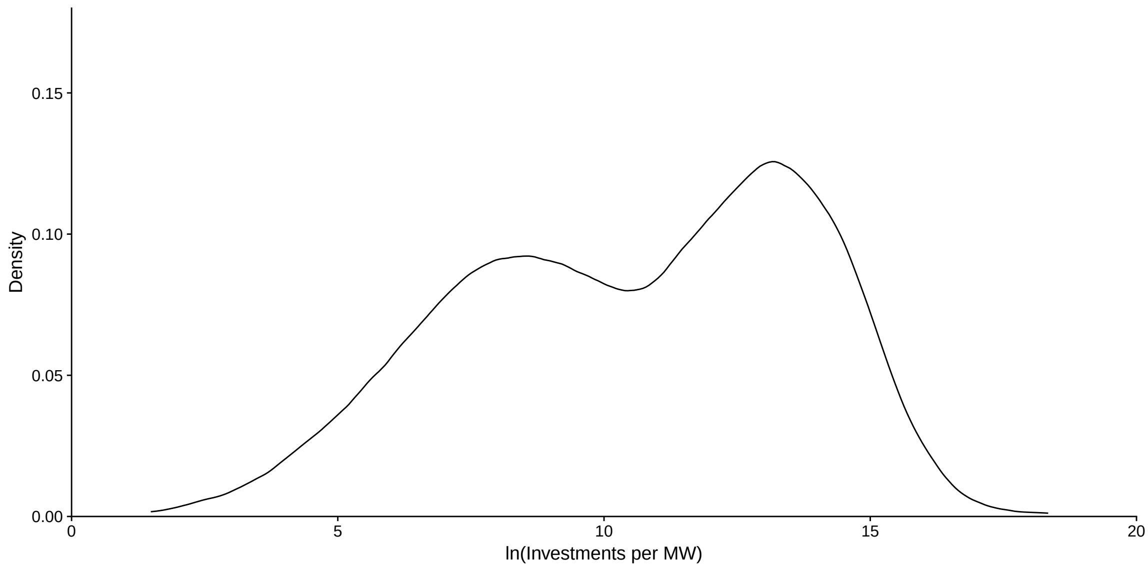

Figure 6: Density of investments in machinery per MW capacity (log)

Notes: This figure shows the kernel density function of investments in machinery per MW capacity transformed by the natural logarithm. Own calculation based on data from Research Data Centre of the Statistical Offices Germany (2016).

Given this distribution, I assume that investment amounts up to 10 (which is around 22,026 Euro per MW and is approximately at the end of the first hump) are only minor investments, which do not influence fuel efficiency. Consequently, I set investments in machinery that qualify as such minor investments equal to zero within an additional specification (column 3 in Table 6).

Dependent Variables:	(1) ln(Inv Machinery)	(2) ln(Inv Machinery (large))	(3) Utilization
ETS Ex-Ante Exposure	0.0221	0.0288^{**}	-0.0053^{***}
	(0.0185)	(0.0129)	(0.0020)
Observations	1,226	1,226	2,577
Time Fixed Effects	+	+	+
Individual Fixed Effects	+	+	+

Notes: In this table the coefficient of the ETS Ex-Ante Exposure obtained in a regression of investments in machinery or utilization on ETS Ex-Ante Exposure spot, year and individual fixed effects as well as on Fuel-Price Ex-Ante Exposure is shown. Heat rate values are trimmed at 2.5/97.5 percent level. Standard errors are in parentheses and clustered at the plant level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 6: ETS Effects on Investment in Machinery and on Utilization

As can be seen in Table 6, ETS Ex-Ante Exposure does not appear to have a statistically significant effect on the level of investment in machinery or only a small positive effect of around three percent on larger investments. ETS Ex-Ante Exposure leads to a reduction in the individual capacity factor (utilization). This is consistent with carbon intensive plants experiencing a steeper increase in their generation cost compared to less carbon intensive plants. This increase is apparently large enough to induce a change in the merit-order. This is in line with Cullen and Mansur (2017), who find that low natural gas prices induced by “Shale Revolution” in the US lead to emission reductions in the US electricity market and present evidence that this observation is consistent with fuel switching from coal to natural gas power plants.

Overall, the findings suggest that the fuel efficiency effects stem mainly from shifts in utilization, i.e. among plants in the merit order based on their carbon intensity, and within plant optimization. Furthermore, there is (weak) evidence for a modest increase in investments into machinery, from which fuel efficiency improvements may also originate.

6. Conclusion

Understanding the impacts on regulated entities is crucial for the assessment and the further development of mitigation policies such as emission trading schemes. The introduction of the EU ETS in 2005 marks the start of the largest cap-and-trade system for greenhouse gas emissions worldwide. In this paper I use the introduction of this policy to contribute to the still scarce empirical literature based on micro data on the effects of carbon pricing on power plants. Given the high share of fuel-related cost in total cost in power generation, the introduction of a carbon price may provide carbon intensive power plants an incentive to improve fuel efficiency. I investigate the impact of the EU ETS on fossil fuel power plants in Germany using administrative plant level data. Thereby, I use variation in carbon cost induced by the introduction of the EU ETS in 2005 and the differential exposure of power plants to carbon prices for identification.

The estimated effects suggest that at average carbon cost of around six Euro per MWh electricity and heat generation, the EU ETS decreases fuel input by around 2.4 percent, while holding output fixed. At an annual fuel input of 750 terawatt hour (TWh) and annual carbon emissions of around 290 million tonnes in hard coal, lignite and natural gas power plants[25], on average this decrease in fuel input is equivalent to a reduction of around seven million tonnes in annual carbon emissions, using the average emission intensity of fossil fuel use in Germany in 2012. The results on fuel efficiency are robust to several specifications. However, one specification, using only single unit generators, suggests that the effects might be driven by power plants with multiple generating units. Nevertheless, it remains unclear whether this means that the effects are originating from adjustments by within-plant optimization among different generation units or whether it is due to (unobservable) structural differences between single and multi generation unit power plants.

Furthermore, given the rather small magnitude of effects, the results hint at the implementation of small-scale and maybe less-capital intensive measures to improve fuel efficiency. This is in line with the findings of either statistically insignificant or small positive effects on investments in machinery. Another possible driver of fuel efficiency is the change in utilization. I find that the ETS negatively impacts the capacity factor, i.e. carbon intensive plants produce less heat and electricity in relation to their potential output compared to less carbon intensive plants. Thus, the small effect should be interpreted as a positive net effect on fuel efficiency, exceeding the potential counteracting negative fuel efficiency effect from decreased utilization of carbon intensive power plants.

Given the empirical framework, I concentrate on the short term reaction to carbon prices. I assume that within each period capital (and thereby investment) or labour cannot be substituted for fuel input. The introduction of a carbon price leads to a change in relative input prices. If short-run substitution between fuel and labour were important in this context, this should also have impacted labour demand. Hence, the statistically insignificant effect of the EU ETS on labour input lends support to the assumptions underlying the Leontief approach. The role of substitution between capital and fuel use, e.g. by investing in newer technology to improve heat rates, may be a more prominent driver for fuel efficiency gains in the long run. However, I do not find evidence that the EU ETS has triggered large investments in machinery even seven years after its introduction. For the years after 2012, carbon prices have remained low compared to prices in the period of this study, making it even less likely that adequate incentives may have prevailed to invest in new technology for fuel efficiency improvements.

[25]These calculations are based on data from UBA (2013).

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Appendix A Heterogeneous Effects on Fuel and Labour Efficiency

While there are three categories available for fuel types (i.e. hard coal, lignite and natural gas), I define size and age categories to allow for non-linear effects. The categories are in line with the empirical distribution and are divided as follows: small (<10 MW), medium (10 to <80 MW), large (80 to <400 MW) and huge (≥400 MW) for the size as well as new (< 10 years), young (≥ 10 to < 20 years), medium (≥ 20 to < 40 years) and old (≥ 40 years) for age. The different categories for fuel types and size classes are interacted with the variable of the ETS Ex-Ante Exposure, respectively.

The effects of the EU ETS on fuel efficiency seems to be quite homogeneous with respect to the main categories, expect for power plants larger than 80 MW (categories "large" and "huge"). For these power plants, the fuel efficiency effect of the ETS Ex-Ante Exposure seems to be somewhat lower in magnitude. As in the case of the average effect in almost all specifications the heterogeneous effects of the ETS Ex-Ante Exposure on labour input is not statistically significant.

Dependent Variable:	(1) ln(fuel)	(2) ln(fuel)	(3) ln(labour)	(4) ln(labour)
ETS Ex-Ante Exposure	-0.0145^{**}	-0.0208^{***}	0.0031	0.0060
	(0.0060)	(0.0063)	(0.0080)	(0.0090)
ETS Ex-Ante Exposure X Medium	0.0026	0.0061	-0.0017	-0.0019
	(0.0035)	(0.0040)	(0.0053)	(0.0051)
ETS Ex-Ante Exposure X Large	0.0076^{**}	0.0115^{***}	-0.0005	-0.0010
	(0.0038)	(0.0041)	(0.0052)	(0.0059)
ETS Ex-Ante Exposure X Huge	0.0071^{*}	0.0109^{**}	-0.0007	-0.0032
	(0.0042)	(0.0044)	(0.0055)	(0.0060)
ETS Ex-Ante Exposure X Young	0.0001	0.0004	0.0033	0.0039^{**}
	(0.0010)	(0.0012)	(0.0026)	(0.0019)
ETS Ex-Ante Exposure X Medium	0.0008	0.0001	0.0023	0.0015
	(0.0010)	(0.0011)	(0.0024)	(0.0018)
ETS Ex-Ante Exposure X Old	-0.0096	-0.0124	-0.0108	-0.01143
	(0.0108)	(0.0101)	(0.0104)	(0.0070)
ETS Ex-Ante Exposure X Lignite	0.0013	0.0023^{*}	-0.0003	-0.0006
	(0.0012)	(0.0013)	(0.0032)	(0.0026)
ETS Ex-Ante Exposure X Natural Gas	-0.0008	-0.0088	0.0055	0.0049
	(0.0034)	(0.0032)	(0.0041)	(0.0040)
First Stage F-Statistic		28.31		33.52
Stock-Yogo critical values (10%)		16.38		16.38
Arellano-Bond test AR(1) p-value	0.007		0.067	
Arellano-Bond test AR(2) p-value	0.822		0.297	
Hansen test p-value	0.669		0.088	
Number of instruments	55	1	56	1
Observations	2,246	2,569	868	994
Instruments	L.q	C.q	L.q	C.q
Time Fixed Effects	+	+	+	+
Individual Fixed Effects	+	+	+	+

Notes: In this table the coefficient of the ETS Ex-Ante Exposure and its interaction obtained in a regression of fuel input or labour input on ETS Ex-Ante Exposure, Fuel Price Ex-Ante Exposure, individual electricity and heat generation, year and individual fixed effects are shown. In the models of labour input in column (3) and (4), wages and available capacity (capital) are additional explanatory variables. Heat rate values are trimmed at 2.5/97.5 percent level. The first column refer to two-step difference GMM estimation using forward orthogonal deviation transformations. Standard errors are in parentheses and clustered at the plant level. Size categories are small (<10 MW), medium (10 - <80 MW), large (80 - <400 MW) and huge (400 MW and more). Age categories are new (<10 years), young (10 - <20 years), medium (20 - <40 years) and old (40 years and more). * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 7: Heterogeneous Effects - Fuel