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SHORT-TERM CO_2 ABATEMENT IN THE EUROPEAN POWER SECTOR: 2005-2006

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ABSTRACT

This paper provides an estimate of short term abatement of CO_2 emissions through fuel switching in the European power sector in response to the CO_2 price imposed by the EU's Emissions Trading Scheme (EU ETS) in 2005 and 2006. The estimate is based on the use of a highly detailed simulation model of the European power sector in which abatement is the difference between simulations of actual conditions with and without the observed CO_2 price. We estimate that the cumulative abatement over this period was about 53 million metric tons. The paper also explains the complex relationship between abatement and daily, weekly, and seasonal variations in load, relative fuel prices, and the price of CO_2 allowances.

KEYWORDS: CO_2 abatement; Electricity generation simulation, European Union Emission Trading Scheme; Fuel switching;

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I. INTRODUCTION

Discussions of the significant reductions in greenhouse gas (GHG) emissions required to mitigate global warming tend to focus on fundamental changes in technology and long-term investments in low- or zero-emitting capital stock. While this emphasis on long-term technological change is well-placed, it can have the effect of ignoring the less spectacular but still important, short-term reduction in GHG emissions that can be obtained with existing capital stock in response to a price on CO_2 emissions. Accordingly, this paper addresses how much short-term abatement can be expected in response to a CO_2 price?

In seeking to answer this question, we look to the power sector where perhaps the greatest potential for short-term abatement exists. Power plants are dispatched on at least an hourly basis in response to load and fuel prices; and they differ significantly in their emission characteristics due both to the fuel used and the efficiency of electricity generation. The specific context for our analysis is the European power sector as it has responded to the price on CO_2 that has been imposed by the European Union's CO_2 Emissions Trading Scheme (EU ETS) in 2005 and 2006.

The literature on abatement in the first, trial period (2005-07) of the EU ETS is sparse, especially from an ex post perspective. Ex ante analyses of the EU ETS abound but relatively few of them provide estimates of expected abatement, or they do so only accidentally or by inference. Most of these ex ante studies were concerned either with showing the cost-savings from EU-wide emissions trading (such as, Kemfert et al., 2005) or the inefficiencies attendant on a hybrid or partial, sectoral approach to trading (Bohringer et al., 2005; Jourdan de Muizon, 2006). Moreover, results reported in many of

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these early studies understandably focused on the more important second trading period from 2008-12 (Klepper and Peterson, 2005; Peterson, 2006). Of those reporting results for the first period, all except Bohringer et al. (2005) obtained a positive European Union Allowance (EUA) price (albeit a low one), which implied abatement of some magnitude.

A research group at the University of Leuven has published a number of papers focusing on fuel switching in the electricity sector based on earlier versions of the E-Simulate model used in the present paper (Voorspools and D’haeseleer, 2006; Delarue et al., 2007; Delarue and D’haeseleer, 2008). While most of these are heuristic in explaining fuel switching and its relation to certain variables, Voorspools and D’haeseleer (2006) estimate that fuel switching in response to a CO_2 tax of 10 euro/ton would reduce CO_2 emissions in the major EU15 economies by 6%.

Two analyses of EU ETS abatement from an explicitly ex post perspective, precede this paper. Ellerman and Buchner (2008) provide an ex post estimate of abatement for the EU ETS as a whole in 2005 and 2006 based on an analysis of the trends in CO_2 emissions and various indicators of economic activity. Although carefully argued, their top-down approach is one of casual empiricism in which an observed break in the trend in CO_2 emissions relative to the trends in economic activity is imputed to the presence of a CO_2 price. On this basis, they estimate EU-wide abatement of 50 million to 100 million tons in each of the first two years of the EU ETS.

Delarue et al. (2008) provide an ex post estimate of abatement through fuel switching in the electricity sector using an expanded version of E-Simulate that includes all of the EU15 and the major new member states in Eastern Europe. Their estimate for abatement for the power sector alone is 88 million tons in 2005 and 59 million tons in

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2006. The ex post perspective is imparted by the use of actual electricity demand and prices for fuels and allowances for 2005 and 2006. Otherwise, it is assumed that the model accurately reflects availabilities and other operating conditions. Implicitly, the assumption is that departures from the assumed, ideal supply conditions in the model would be such as not to affect significantly the differences in dispatch and emissions occasioned by the carbon price

This present paper differs from Delarue et al. (2008) by calibrating E-Simulate to observed conditions in the years immediately preceding the start of the EU ETS. In fact and as will explained presently, calibrating the model to actual supply conditions makes a significant difference in the estimate of abatement, at least in this instance.

The presence of abatement in the EU ETS has been obscured by the ex post surplus position of the EU ETS in the trial period (“over-allocation”), which is often erroneously assumed to imply no abatement. Although several observers pointed out that the proposed member-state caps were potentially non-binding (Betz et al., 2004, in addition to Bohringer et al., 2005), initial EUA prices were much higher than predicted in all ex ante analyses. They remained positive for almost a year after the first release of verified emissions data in April-May 2006, which revealed that emissions were significantly lower than expected. Among other things, Ellerman and Buchner (2008) point out that abatement and over-allocation are not mutually exclusive and that both occurred. In the present paper, the focus is exclusively on short-term abatement (e.g., without considering changes in the capital stock) on the assumption that agents respond to prices and not to the EU-wide cap, which has no practical meaning at the plant level. Moreover, to the extent that abatement did occur, the end-of-period surplus was that

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much greater.

The paper proceeds as follows. The next section of the paper provides a description of the model that is used to simulate the European power sector and its response to a carbon price. Such a model is required to establish a counterfactual estimate of what CO_2 emissions would have been without a carbon price. This section of the paper also conducts a calibration of the model to actual generation and emissions data for 2003 and 2004, before a carbon price was present. As noted above, this calibration allows an evaluation of the extent to which actual practice departs from the assumptions that are necessarily made in any model and the effect of those departures on estimates of abatement. The third section of the paper presents estimates of short-term abatement in the European power sector in response to the CO_2 price imposed by the EU ETS. This price varied greatly (between about 30 and 0 euro/ton) during the three years of the first trading period corresponding to the calendar years 2005 to 2007, as did the price difference between the two principal generation fuels, natural gas and coal. In the final concluding section, we return to the issues raised at the beginning of the paper and seek to generalize from the European experience.

II. MODEL DESCRIPTION AND CALIBRATION

A. *The E-Simulate model*

The European electricity system is modeled using E-Simulate, which was developed at the University of Leuven (Voorspools, 2004).[1] This model simulates

[1] For further details on E-Simulate, the reader is referred to Voorspools (2004) and Voorspools and D'haeseleer (2006).

electricity generation dispatch on an hourly basis over an annual cycle at the power plant level.[2] The entire system is organized as a set of interconnected 'zones', each of which corresponds to a specific country or group of countries. Transfers of electricity can occur among zones subject to the pre-specified limits on interconnection capabilities. The demand for electricity is specified by zone for each hour of the year and the model solves for the least cost dispatch of generation to meet electricity demand in all zones. Thus, E-simulate operates as a linked hourly stacking model in which the stacking of available generation is determined by power plant characteristics and fuel prices. The output of the model consists of the electricity generation of each power plant for each hour of the simulated time span. Corresponding CO_2 emissions are made part of the output by attaching emission coefficients to plants according to fuel use and plant type. The CO_2 price is treated as an additional cost for a specific fuel that depends on the fuel's carbon content and the assumed efficiency with which electricity is generated at each plant. The CO_2 price will change the stacking order of the power plants in each zone and therefore, the outcome with respect to generation and emissions.

Several corrections are made in the dispatch algorithm in order to respect the technical characteristics of the power plants (minimum operating point, minimum up- and downtimes). To correctly represent the limited availability of power plants, a 'derated' power approach is used. Thus, a 100 MW plant that is available 90% of the time is assumed to have constantly $100 \text{ MW} \cdot 0.9 = 90 \text{ MW}$ available for all hours of the year. The availability factor reflects possible forced outages. In addition, power plants face a

[2] The model actually simulates a full year on an hourly basis, i.e., 8760 hours. No aggregation over hours is made.

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scheduled outage for maintenance and a requirement for reserves is also enforced in the model.

Trade in electricity within and between zones is based strictly on economic incentives. Subject to the capacity constraints on interzonal transfers, neighboring zones are always potential suppliers to demand within any given zone depending on the relative cost of incremental generation within the zone and from neighboring zones. Kirchhoff's laws are not taken into account either within zones or for flows between zones, nor are transmission constraints assumed to exist within zones.

Several specific types of power plants are dealt with prior to the optimization process in a way that their utilization is fixed at the observed values. These are cogeneration plants, which are heat-driven, and single storage hydro reservoirs and pumped storage units, both of which are used for peak shaving.

<TABLE 1 HERE>

E-simulate models 21 European countries in a 10 zonal configuration as presented in Table 1. This implementation has been chosen to represent the main players adequately and to represent Europe's bottlenecks in transmission. Eight of the European Union's twenty-seven member states are not modeled: the three Baltic member states; Greece, Cyprus, and Malta because of their lack of integration with the main European grid; and Bulgaria and Romania which became member states only in 2007. Two non-EU member states, Switzerland and Norway, are included because of their close integration with neighboring EU member states in the daily operation of the European electricity grid. The excluded EU countries account for only 6% of EU electricity sector emissions in 2005-2006 and the included non-EU members, i.e., Switzerland and Norway, have negligible

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CO_2 emissions.

B. *Calibrating to actual conditions*

In its standard form, E-Simulate makes a number of assumptions that may be seen as unrealistic for at least some parts of the European electricity system. For instance, it assumes that the prices paid for fuels by generators and therefore used in dispatch decisions are uniform throughout the 21-country region that is modeled.[3] The model also assumes that wholesale markets have been completely liberalized and that perfectly competitive conditions prevail throughout. Finally, while operational constraints are incorporated into hourly dispatch, contract considerations are not; and all plants throughout Europe operate at standard availabilities.

While these departures from actual conditions are typical of modeling exercises and none disqualify E-Simulate from providing a realistic view of the short-term response of the European electricity system to a carbon price, a question always remains concerning the extent of the departure from actual conditions and the consequent effect on estimates of short-term abatement in response to a carbon price. Accordingly, a calibrated version was developed in which E-Simulate was run using demand conditions

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[3] Uniform in this case means 'uniform throughout Europe'. The fuel prices used are still daily prices that vary considerably over the course of the year. This assumption of uniform prices holds for coal and petroleum products, but it might be questioned for natural gas. While a price convergence between the UK and the Zeebrugge Hub (Belgium) can be demonstrated, some differences can still exist, such as between Zeebrugge and Bunde (Dutch-German border) (Neumann et al., 2006). However, on a longer time frame and considering yearly data, evidence of converging prices throughout Europe can be shown (Robinson, 2007).

in 2003 and 2004, the output compared with observed dispatch, and adjustments made to minimize the divergence from actual supply conditions.[4] These adjustments were retained for 2005-2006 on the assumption that they persisted in the simulation years of 2005 and 2006.

A clear general tendency can be observed in these adjustments. In nearly every zone, the unadjusted model is predicting more coal and lignite use at the expense of natural gas and oil than was actually the case in 2003-04. For the 21-country system, E-Simulate yields a coal/lignite share of 34% in 2003 and 31% in 2004, when in fact these shares were 29% and 28%, respectively. Conversely, it posits natural gas/oil shares of 17% in 2003 and 20% in 2004 compared to actual shares of 22% and 23%, respectively.

A number of factors could cause these divergences but most can be summarized as less availability of the coal and lignite plants than what is suggested by the standard availability factors. Lower availability could be the result of technical difficulties at the plant, lack of sustained maintenance, or lack of fuel. Other explanations can be possible constraints on emissions (e.g., NO_x, SO_x), or the need for large amounts of modulation power, to deal with fluctuating power output of wind turbines, as neither these constraints on emissions nor this wind fluctuation is modeled. Also, natural gas or coal prices that differ from the uniform price assumed in the model, the National Balancing Point (NBP) gas price and ARA coal price, could lead to this result. However, in the zone that is most liberalized (the UK), the unadjusted simulation also predicted more coal and less gas use than was actually the case. Accordingly, the main correction in developing the "calibrated" model is to adjust coal and lignite availabilities downward and only

[4] Details of the calibration are available from the authors upon request.

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secondarily to introduce factors that would change the price of certain fuels.

The most important changes were the following:

Zone 1 (UK, Ireland): Decrease in the availability of coal fired power plants by 31%;

Zone 2 (Iberian Peninsula): A different (daily) price for natural gas[5];

Zone 5 (Italy): A different (daily) price for natural gas[6];

Zone 7 (Poland): Decrease in the availability of coal and lignite fired power plants by 25% and 22%, respectively;

Zone 8 (Central East Europe): Decrease in the availability of coal and lignite fired power plants by 23% and 45%, respectively;

Zone 10 (Germany): Decrease in the availability of coal and lignite fired power plants by 8% and 10%, respectively.

Pertinent simulation results for both the unadjusted and the calibrated models are presented in Table 2. Electricity generation over the whole year is grouped per fuel and aggregated over all the zones modeled. The electricity generation is expressed as a fraction of the total share, with a very good match between the calibrated model and actual numbers.

<TABLE 2 HERE>

Cross-border or inter-zonal flows were not used for calibration since they are an order of magnitude smaller than actual generation. Nevertheless, the calibration improved

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5 This change links the gas price to the oil price profile, thereby also resulting in a gas price that was on average higher than the NBP price.

6 Ibid.

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the correspondence between actual and modeled flows.

III. ESTIMATES OF SHORT-TERM POWER SECTOR ABATEMENT IN 2005 AND 2006

We now turn to the calibrated version of E-Simulate to provide estimates of abatement due to the carbon price in 2005 and 2006. The year 2007 is not included due both to the lack of data on zonal demand and generation for this year when this analysis was performed and to the low level of the EUA price in 2007. Figure 1 presents the EUA price as it evolved during the first period (2005-2007).

<FIGURE 1 HERE>

The model is run for both 2005 and 2006 using actual zonal demand and energy prices both without a carbon price and with the actual CO_2 prices. The zero CO_2 price case provides a counterfactual estimate of what emissions would have been without the EU ETS. The difference between this estimate and the corresponding model run with the actual EUA price provides the estimate of abatement or CO_2 reduction that we be attributed to the EU ETS.[7]

A. *Aggregate abatement and the effect of calibration*

One convenient way to illustrate the effect of a carbon price is to show the monthly share of coal-fired generation in total supply as is done in Figure 2.

[7] It should be kept in mind that renewable energy generation is fixed at actual values in both cases and zonal energy demand is likewise invariant so that the effects of renewable energy and of energy conservation measures will not affect estimates of abatement.

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<FIGURE 2 HERE>

A seasonal effect can clearly be observed. [8] When a carbon price is present, the coal share drops noticeably during the summer months. The explanation is that Europe's winter-peaking electricity system requires that a lot of the gas-fired capacity be used to meet demand during the winter and is therefore not available for dispatch in response to a carbon price. In the summer, when demand is less, the more expensive gas-fired capacity is available and capable of displacing coal-fired generation when a carbon price is sufficiently high to warrant the substitution.

Figure 3 presents the CO_2 emissions and the abatement for all zones aggregated on a monthly basis for these same years. Again, the pattern of abatement is high seasonal with most of the abatement during the year occurring in the summer because of the greater availability of otherwise unused gas-fired capacity. Less abatement occurred in 2006 because of the interaction of carbon and fuel prices. As shown by Figure 1, carbon prices were much higher in the summer of 2005 than in the summer of 2006.

<FIGURE 3 HERE>

The summary EU-wide results for abatement are presented in Table 3 below. These figures are the sums of the monthly plots on Figure 3. These estimates for CO_2-price-induced abatement from the power sector, 34 million tons in 2005 and 19 million tons in 2006 are equal to about 1.75% and 1.0% of EU-wide capped emissions and about 3.0% and 1.7% of power sector emissions.

[8] The pattern in 2006 is less distinct because of the significant decline in EUA prices after the release in late April of verified emission reports, which revealed that emissions were much lower than generally assumed.

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<TABLE 3 HERE>

When considering this estimate of abatement, it is important to remember that the calibration implicitly assumes that whatever constrained plant availabilities in 2003 and 2004 continued to do so in 2005 and 2006. While some factors, such as plant-specific lower availability or efficiency, could be expected to remain constant, other factors, such as temporary shut-downs due to some malfunction or maintenance problem in 2003 or 2004, would typically not be applicable in 2005-06. One way to check for the persistence of the constraints on coal use revealed by the calibration is to compare simulation results of both the unadjusted (non-calibrated) and calibrated model with actual outcomes in 2005 and 2006. If the calibrated case is closer to observed values, then more confidence can be placed in the assumption that the calibration is reflecting continuing, pre-existing constraints on coal plant utilization.

Table 4 compares the unadjusted and calibrated simulation results for 2005 and 2006, assuming actual EUA prices, with actual EU-wide generation shares, as was done in Table 2 for 2003-2004.

<TABLE 4 HERE>

In this comparison, the unadjusted (non-calibrated) versions of the model over-predict the amount of coal use and under-estimate the amount of natural gas use in both years. The calibrated simulations almost perfectly match observed fossil-generation shares. This suggests again that simulations with the adjusted model are closer to reality. In fact, estimates of abatement are approximately halved due to the reduced availability of idle gas capacity to replace higher emitting coal generation.

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B. *The Timing of Abatement*

Abatement is mainly determined by the following three factors: the EUA price, the gas-coal price ratio and the load level of the power system. A direct relationship between the EUA price and abatement is what would be expected: all else being equal, a higher EUA price would elicit higher CO_2 abatement. However, the magnitude of abatement that will occur for any given EUA price is powerfully conditioned on the gas-to-coal price ratio and the load level.

For abatement to occur, the gas-to-coal price relation must be neither too low (gas fired electricity generation would be preferred over coal fired generation anyway) nor too high (gas prices are so high that coal-fired generation is favored even with a price on CO_2 emissions). Thus, for any given range of expected or observed EUA prices, abatement occurs only within some intermediate range for the gas-to-coal price ratio.

The amount of abatement associated with any given EUA price is also heavily influenced by load, especially when coal-fired generation is cheaper than gas-fired generation and thus dispatched first, as is generally the case. Since unused low emitting generation capacity must be available for switching to occur, periods of low load are more favorable for abatement than periods when demand peaks and the system is tight, with practically all plants running at full capacity.

The interaction between these three determinants is highly complex, and is discussed methodologically in Delarue et al. (2010).[9] These relationships explain both

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[9] The reader is also referred to the following articles. The specific effect of the load level on abatement is discussed for a specific case study (Belgium) in Delarue and D'haeseleer (2007), and for 8

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the seasonal nature of abatement, noted in Figures 2 and 3, and its high variability even within a given season.

Figure 4 depicts the daily relationship between abatement, the EUA price and fuel prices as the latter evolved through 2005 and 2006. Each plot point is a daily value for the EUA price (dashed line), simulated abatement (jagged solid line), and the switching band (in gray), which reflects daily coal and natural gas prices. This switching band is constructed as follows. The EUA price required to switch a certain coal and gas plant in the merit order depends on the gas and coal prices, the efficiencies of the two plants, and the carbon content of both fuels as shown in equation (1) below. Let η_c be the coal plant's efficiency; η_g be the gas plant's efficiency; FC_c the fuel cost for coal [euro/GJ]; FC_g the fuel cost for gas [euro/GJ]; EF_c the emission factor of coal [tonCO_2/GJ]; and EF_g the emission factor of gas [tonCO_2/GJ]; then the allowance cost, ACs [euro/tonCO_2], necessary to switch both plants in the merit order is:

$$ACs = \frac{\eta_c \cdot FC_g - \eta_g \cdot FC_c}{\eta_g \cdot EF_c - \eta_c \cdot EF_g} \qquad (1)$$

The lower bound of the switching band presents the allowance cost required to switch a relatively more efficient gas plant (50%) for a relatively inefficient coal plant (36%), calculated with fuel prices of the actual day. The upper bound is set at the switching point for a relatively inefficient gas plant (36%) and a relatively efficient coal plant (38%).

Western European countries in Delarue and D'haeseleer (2008). The effect of a varying natural gas price on abatement is studied in Delarue et al. (2007). The three determinants might show mutual relationships themselves. The relationship between EUA and natural gas prices is discussed in, e.g., Mansanet-Bateller et al. (2007), Bunn and Fezzi (2007), and Alberola et al. (2008).

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Thus, whatever the load, most of the abatement from fuel switching will occur when EUA prices are situated in this band.[10] When EUA prices are below this band, little abatement can be expected and, when they are above the switching band, nearly all switching opportunities will be used and little additional abatement can be expected at higher CO_2 prices.

<FIGURE 4 HERE>

The effects of load are readily evident in the daily abatement estimates.

- Most of the abatement occurs between April and October because the lower seasonal load during these months makes more unused gas generating capacity available for switching. This effect of seasonal load on abatement is, however, not visible as an isolated effect since the gas/coal price ratio is typically also more favorable for switching in these periods.
- The jagged abatement line reflects the difference between demand on week-days and week-ends, which is especially pronounced during the summer. Again, the cause is the availability of more gas capacity for switching. Since both fuel and CO_2 prices are typically little changed between week and weekend days of any given week, the isolated effect of load on abatement is clearly demonstrated.
- Although not shown here because of the daily frequency, the same

[10] This band is only an indication of what the EUA price should be to expect fuel switching. Fuel switching could already occur at lower EUA prices, for example when the efficiency of the gas plant would be higher than the value used to calculate the lower bound. Abatement can also result from switching that occurs between fuels other than gas and coal, such as lignite to coal, or fuel oil to natural gas.

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consideration operates between day and night time hours, as shown in Table 5 along with the average daily difference between week and week-end days.

<TABLE 5 HERE>

The seasonal and weekly effect of load on abatement is especially pronounced because the most efficient gas plants are committed first regardless of the carbon price. Thus, as demand is reduced, not only is more gas capacity made available but that capacity is more efficient (relative to already idled gas capacity) and thus requiring less of an incentive in the form of the EUA price to substitute for the cheaper but still less efficient coal plants otherwise remaining on line.

The effect of the fuel price spread is also readily evident from Figure 4. For instance, when the fuel price ratio was particularly favorable to switching for a brief period in June 2006 and for a longer period in the fall of 2006, abatement increased markedly, even though EUA prices were relatively low. Similarly, when fuel prices were least favorable to switching, in March 2005 and from November 2005 through March 2006, noticeably less abatement is observed.

The effect and relative importance of the EUA price can be observed over the period from April through June 2006. As the EUA price rose to 30 euro/ton in mid-April with relatively unchanging fuel prices, abatement also rose, only to fall significantly along with the EUA price in late April. Still, despite the low EUA price in May, abatement was about the same as in early April when the EUA price was some 50% higher because the reduced seasonal load made more gas capacity available to substitute for coal. Then in June 2006, a sharp increase in abatement can be observed in response

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both to the more favorable fuel price ratio and the lower demand.

Table 6 presents values for the average generation level, gas/coal price ratio and allowance price split up on a quarterly basis for the years 2005 and 2006. This table clearly shows that abatement occurs mainly in summer, due to a combination of lower load and lower gas prices. For both 2005 and 2006, between 70% to 80% of the abatement for the whole year occurred in the second and third quarters.

<TABLE 6 HERE>

When comparing 2005 with 2006, there was more abatement in 2005 for the first three quarters of the year because of the more favorable fuel price ratios. For the fourth quarter, the situation reverses. The much lower natural gas prices in the fourth quarter of 2006 led to more abatement than in the year-before quarter.

C. *Geographic distribution of abatement in the EU ETS*

The geographic distribution of abatement within the EU power system is not uniform, as might be expected from what has been discussed already. The spatial distribution of abatement will depend on not only where the emissions are, but also and more importantly on the capacity and utilization of gas and coal-fired generation. Figure 5 presents abatement by the E-Simulate zones for 2005 and 2006 in both absolute and relative terms.

<FIGURE 5 HERE>

The bulk of the abatement occurs in the UK with Germany in second place but well behind. The reason is not higher coal-fired emissions in the UK than in Germany, but more gas-fired capacity. Both countries have large coal-fired generating capacity—the UK with about 30 GW and Germany with 50 GW (including lignite)—but the UK has

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more gas-fired capacity, 30 GW, in contrast to the 20 GW in Germany of which about half is CHP and therefore typically not part of the gas-fired capacity that can be readily switched when the economic incentives are right. When compared in relative terms, the UK is still the location of the largest percentage reduction, but the other zones are more equal with reductions usually around 2% of BAU emissions.

The model's abatement results for the UK can be compared with the estimates provided by McGuinness and Ellerman (2008), who estimate abatement from fuel switching in the UK by an econometric approach. Their estimate of abatement is between 13 and 21 Mton in 2005 and 14 and 21 Mton in 2006. E-Simulate's 2005 abatement result for the UK of 16.3 Mton lies in the range reported, while the abatement in 2006 (8.6 Mton) is lower. Both papers agree in finding clear evidence of abatement through fuel switching in response to the EUA price.

The geographic distribution of abatement also reflects inter-zonal transfers. Most of the abatement occurs through switching from coal to natural gas generation within each zone, but a non-negligible share comes from changes in inter-zonal trade. These changes reflect the different intensities of generation in different zones.

The CO_2 intensity of generation in France, the Nordic countries, and Austria-Switzerland is very low and that of Poland very high. The other zones differ by lesser amounts. While the presence of a carbon price causes slight changes in nearly all cross-border trades, the increases in French exports and the decreases in German and Polish power exports have the largest effect on CO_2 emission reduction. Table 7 presents the five most important changes in cross-border flows for both 2005 and 2006 and their

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emission reduction effects.[11]

<TABLE 7 HERE>

The total emission reduction due to inter-zonal transfers constitutes only about 10% of total EU-wide emission reduction for these years. Nevertheless, the effect of the carbon price in redistributing generation from zones with relatively higher emission intensities to those with lower intensities is evident. As reflected in the reverse flow from France to the UK in 2005, some of the changes in cross-border trade flows increase CO_2 emissions, but generally they do not. These six principal carbon-reducing flows account for all of the emission reduction due to inter-zonal transfers in 2005 and 2006. The other flows tend to be slightly carbon increasing and none are of the same magnitude or importance from a CO_2 emission standpoint as these six.

IV. SUMMARY & CONCLUSION

This paper provides an estimate of the short-term abatement of CO_2 emissions through the re-dispatch of existing generating capacity in response to the carbon price established by the EU ETS. To do so, a detailed simulation model, E-Simulate, developed at the University of Leuven, has been used. This model captures much, but not all, of the highly complex operation of any electricity generation system. Notably, it reflects the capacity, fuel use, and technology of every generating plant in the system and it resolves dispatch to meet demand on an hourly basis. To simulate the conditions that existed in 2005 and 2006, the model is constrained to meet actual demand by zone for each hour

[11] The details of the calculations concerning abatement from changes in inter-zonal transfers are available from the authors upon request.

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given the capacity in place for that year and observed daily fuel prices. Estimates of abatement are formed by taking the difference between runs that incorporate the actual daily CO_2 prices and a hypothetical counterfactual in which there is no CO_2 price.

A distinctive feature of this paper compared to earlier simulations (Delarue et al., 2008) is the calibration of model results to actual generation shares as they were observed in the two years prior to the introduction of a CO_2 price in Europe. This calibration has a significant effect on estimates of abatement. Coal plants were not dispatched as much as the unadjusted model predicted in the calibration years of 2003 and 2004. This could reflect non-fuel price conditions that are unique to the calibration years, but also and more probably other limitations that are continued into the simulation period and that reflect plant idiosyncrasies or other constraints (e.g. regulatory) that limit the use of these plants. Comparison of the calibrated model with actual plant-level generation in the ETS years supports the assumption that the reduced coal plant availability observed in 2003 and 2004 continued into 2005 and 2006. These pre-existing and continuing limitations on coal use reduce the resulting estimates of abatement in response to a CO_2 price significantly, compared to estimates obtained with an unadjusted (non-calibrated) model.

The estimate for cumulative abatement in response to the EU ETS in 2005 and 2006 is 53 million tons. There is a distinct temporal and geographic distribution of this abatement. Temporally, most of the abatement occurs during the summer months and throughout the year during week-ends and at night when demand is lower and more unused gas-fired capacity is available for switching. Geographically, most of the abatement through fuel switching in the EU occurs in the UK and Germany where a significant reliance on coal is coupled with available natural gas generating capacity.

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Finally, most of the abatement takes place through fuel switching within each zone, although a noticeable increase in inter-zonal power transfers from lower emitting generation in France at the expense of higher emitting generation in Germany and Poland can be observed.

The results of any modeling exercise, such as those presented in this paper, are the result not only of the features specifically modeled but also of the underlying assumptions. In closing, we draw the readers' attention to three of these maintained assumptions that could provide the basis for further research. In order of importance, these are: 1) a fully competitive market for wholesale electricity throughout the EU, 2) uniform market prices for coal and natural gas that ignore transportation cost differences and contractual considerations, and 3) the effects of the loop-flow constraints that often affect the dispatch of power plants in an electricity grid. While taking these conditions into account would likely affect the magnitudes of the abatement estimates, we doubt that they would negate the finding of abatement through fuel switching in response to a positive price on CO_2. Moreover, the general patterns of abatement resulting from the complex interactions between the CO_2 price, fuel prices, and load seem likely to persist regardless of regulatory treatment, more accurate fuel prices, and more sophisticated grid modeling. In particular, the extreme variability of the amount of abatement through fuel switching that can be associated with any given CO_2 price, as a result of the complex interaction with fuel prices and load, is unlikely to change. This alone should give pause to anyone imagining a clear, simple, and unconditional relationship between CO_2 price and abatement.

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APPENDIX ON DATA AND SOURCES

A large amount of historical data is available from different sources, and a significant range exists for certain numbers due to a slight difference in the exact definition (e.g., the voltage level at which supply or demand is measured). In this work, an attempt is made to rely as much as possible on a coherent data set, resulting from a limited number of different sources. For the time dependent data (everything except power plant characteristics), data is gathered for the years 2003, 2004, 2005 and 2006.

1. Technical characteristics of power plants

The following characteristics are given for each type of power plant (sub-critical coal steam, combined cycle natural gas, etc.): minimum operating point (as a percentage of the nominal capacity), the heat rate curve, i.e., the plant's efficiency at partial load (again described in percentages of the nominal capacity and efficiency), minimum up- and downtime, and country-specific estimated availability allowing for planned outages. The data for each type of power plant are based on generally available engineering specifications that are then checked against the experience of operating utilities and available data on performance (Voorspools, 2004; Wood and Wollenberg, 1996; World Energy Council, 2004).

2. Power system

The electricity generation systems of all the countries modeled are based upon the EURPROG 2006 report of Eurelectric (2007). Given the electricity generating capacity for each country and year per fuel and per type, together with the amount of CHP installed per fuel, an accurate representation of each power system can be created on power plant level that matches the amount of installed capacity by fuel as well as the installed amount per technology. Historical data is available for both the years 2003 and 2004, while for 2005 and 2006 the commissioning capacity, i.e., new capacity coming online, is given.

3. Load

For the countries modeled that were a member of the former Union for the Co-ordination of Transmission of Electricity (UCTE), i.e., AT, BE, CH, CZ, DE, ES, FR, HU, IT, LU, NL, PL, PT, SL and SK, hourly load data for 2006 is taken from the ENTSO-E website (ENTSO-E, 2009). For the other years, these profiles are scaled to match both total and peak demand. This total electricity consumption and peak load is also taken from ENTSO-E (2009). The load of Denmark, Finland, Sweden and Norway is taken from Energinet.dk (2007), Fingrid Oyj (2007), Statistics Sweden (2007), and Statnett (2007) respectively. The load of the United Kingdom and the Republic of Ireland is provided for by National Grid (2007) and Soni (2007), and Eirgrid (2007), respectively. Also for the non-UCTE countries, for the years when no hourly load is available, the profile of the closest year or of a similar country is scaled to preserve both total load and peak demand.

4. Net Transfer Capacities

For all the years modeled (2003-2006), NTC values are taken from the ENTSO-E (2009).

5. Fuel and EUA prices

The following fuel and carbon prices have been used, on a daily basis (note that these prices do not include transportation cost):

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- Coal: API#2 coal (McCloskey index for coal), first month;
- Natural gas: NBP UK gas (National Balancing Point), day ahead;
- Oil: ICE gasoil (Intern Continental Exchange), front month;
- EUA: Powernext CO_2.

For nuclear, a constant fuel cost of 0.75 euro/GJ has been assumed.

6. Historical generation and emissions data, and cross border flows

Historical generation data can be split up in data that are taken into account in the model as input, data that are used for calibrating the model and data used to validate results for 2005 and 2006. The first set of data consists of the following data, collected for the years 2003-2006, per zone, per fuel, aggregated over the year: the amount of nuclear generation, electricity from renewables (hydro, wind, biomass, photovoltaics and geothermal) and electricity from waste. These data are taken for the years 2003 and 2004 from Eurelectric's EURPROG 2006 report. For the years 2005 and 2006 these data are gathered from diverse sources: ENTSO-E (2009), Energinet.dk (2007), Statistics Finland (2007), Statistics Sweden (2007), Statistics Norway (2007) and the Department for Business Enterprise & Regulatory Reform BERR (2007).

The second part of historical data is the one used for calibrating the model, i.e., the electricity generation from fossil fuels, for the years 2003 and 2004. The numbers for these years are taken from Eurelectric (2007).

Data used for the validation (section III A) of the 2005 and 2006 simulations result from Eurelectric's EURPROG 2007 and EURPROG 2008 reports (Eurelectric 2008 and 2009).

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Figure 1. The EUA price, 2005-2007

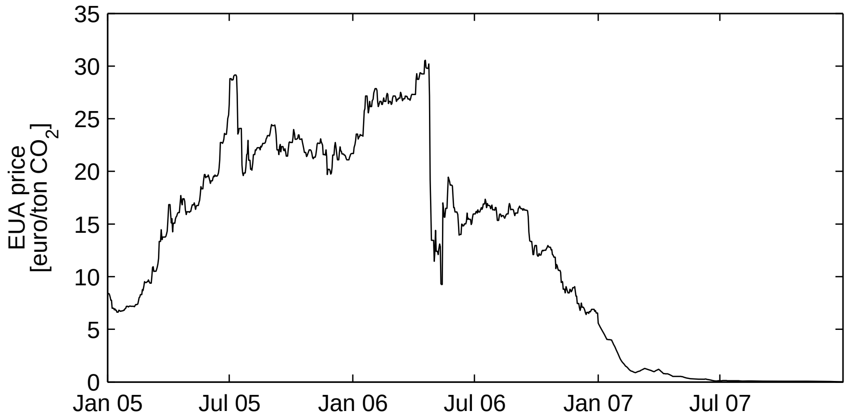

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Figure 2. Share of coal-fired generation in response to EUA prices, 2005 (a) and 2006 (b). The legend in panel (b) also applies to (a).

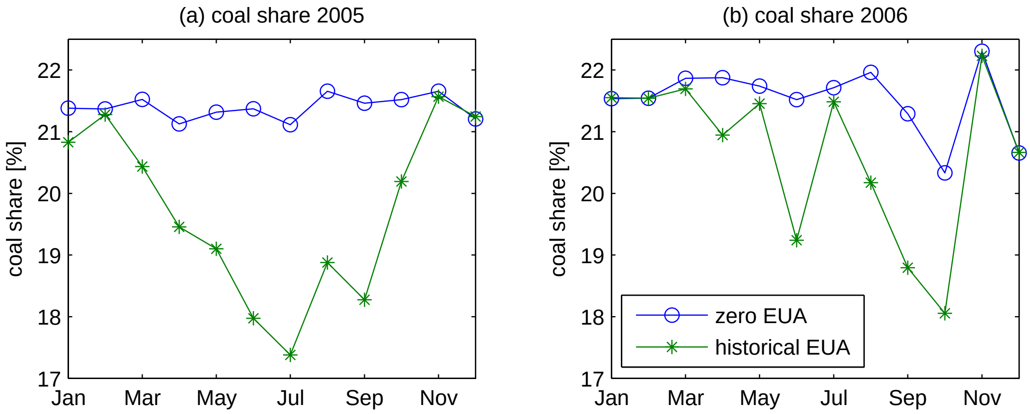

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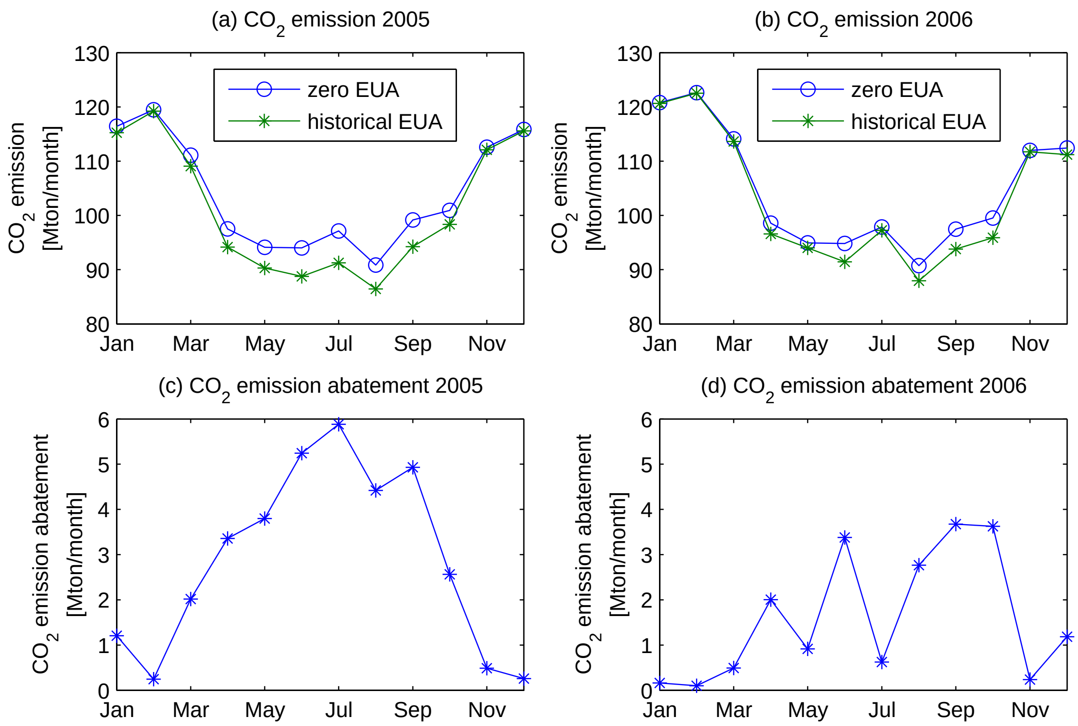
Figure 3. Monthly CO_2 emission and emission abatement in response to EUA prices, 2005-2006.



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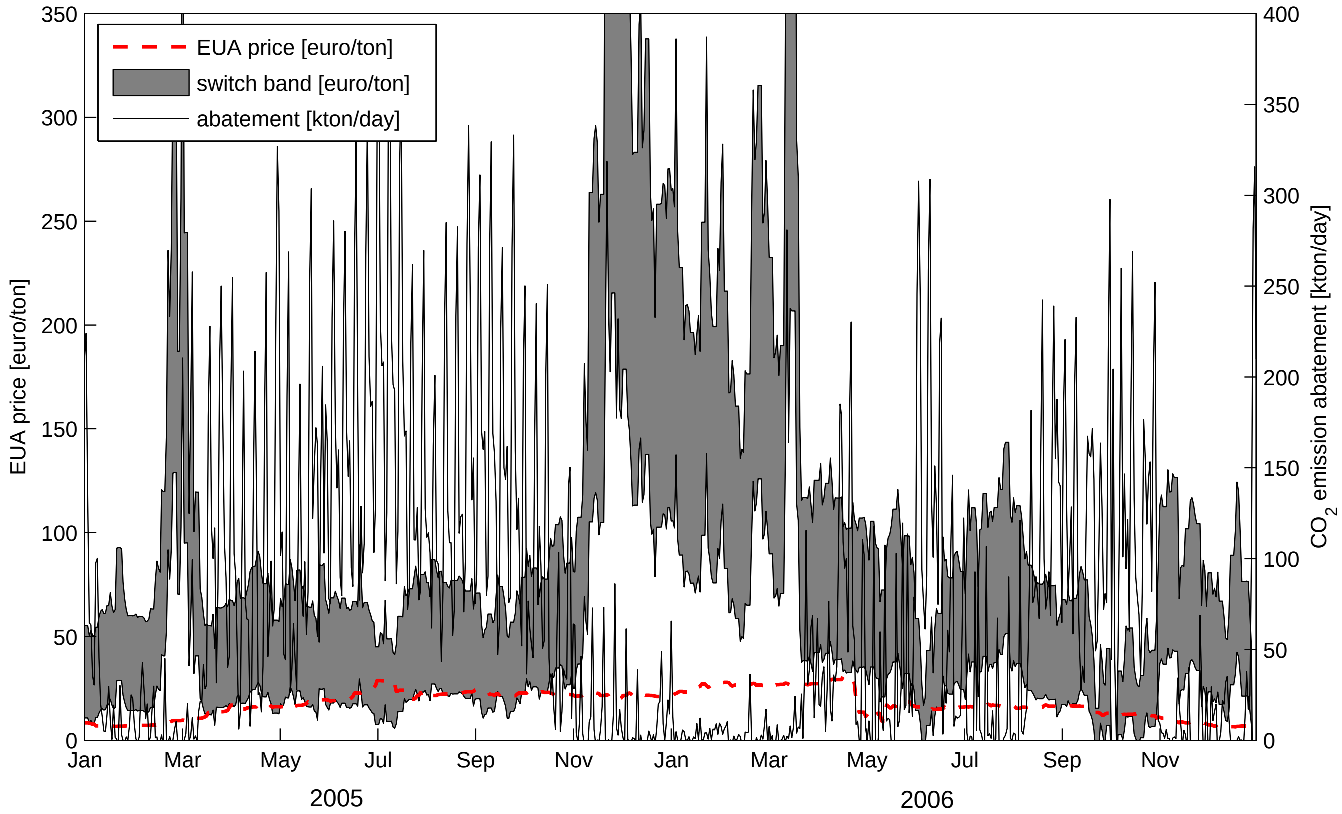
[http://www.worldscientific.com/worldscinet/cce]

Figure 4. Daily abatement, the EUA price and the switching band, 2005-2006.



Note: The switching band is calculated using actual daily prices for natural gas and coal with a lower bound based on a 50% efficient natural gas plant and a 36% efficient coal plant and an upper bound based on a 36% efficient gas plant and a 38% efficient coal plant.

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Figure 5. Geographic distribution of abatement, 2005-2006, (a) absolute reduction and (b) relative reduction.

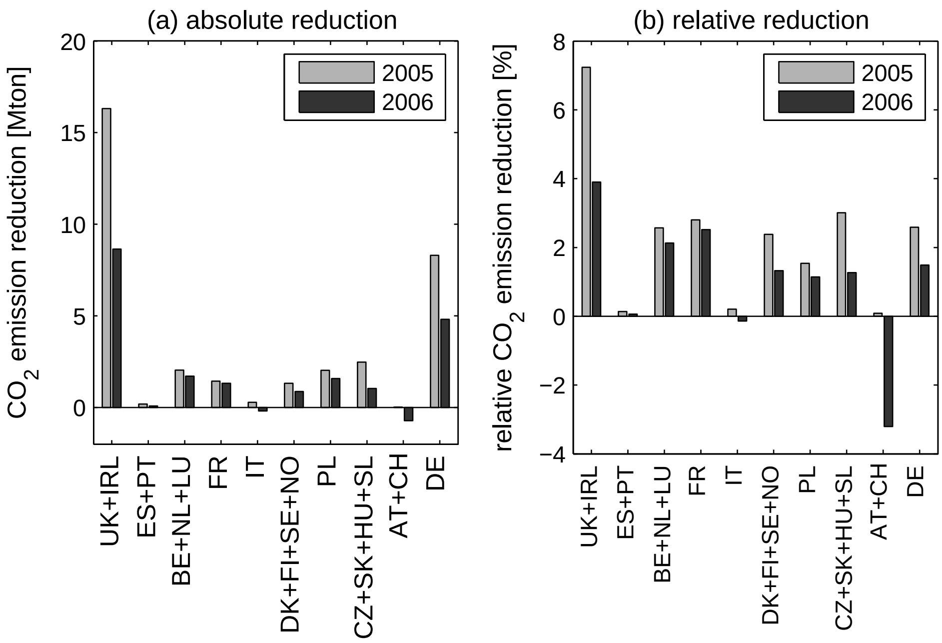

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Table 1. Composition of the different zones considered in the model.

Zone	Countries
1	United Kingdom (UK), Ireland (IRL)
2	Spain (ES), Portugal (PT)
3	Belgium (BE), the Netherlands (NL), Luxembourg (LU)
4	France (FR)
5	Italy (IT)
6	Denmark (DK), Finland (FI), Sweden (SE), Norway (NO)
7	Poland (PL)
8	the Czech Republic (CZ), the Slovak Republic (SK), Hungary (HU), Slovenia (SL)
9	Austria (AT), Switzerland (CH)
10	Germany (DE)

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Table 2. Comparison of historical and simulated electricity generation, for all zones aggregated, in 2003 and 2004, as share in total generation [%]. Simulation results are presented for both the unadjusted and calibrated model.

	nuclear	coal	lignite	gas	oil	hydro	oth. ren.	other
				2003				
Historical real	31%	20%	9%	18%	4%	13%	3%	2%
Unadjusted	31%	23%	11%	15%	2%	13%	3%	2%
Calibrated	31%	21%	9%	18%	4%	13%	3%	2%
				2004				
Historical real	31%	19%	9%	19%	4%	13%	4%	2%
Unadjusted	31%	20%	11%	18%	2%	13%	4%	2%
Calibrated	31%	19%	9%	20%	3%	13%	4%	2%

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Table 3. Estimate for CO_2 emission abatement in the EU for 2005 and 2006.

	CO_2 emission abatement [Mton]
2005	34
2006	19
Total	53

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Table 4. Comparison of historical and simulated electricity generation, for all zones aggregated, in 2005 and 2006, as share in total generation [%]. Simulation results are presented for both the unadjusted and calibrated model (taking into account historical EUA prices).

	nuclear	coal	lignite	gas	oil	hydro	oth. ren.	other
				2005				
Historical real	30.1%	18.4%	8.6%	19.8%	3.4%	13.7%	4.0%	1.9%
Unadjusted	29.8%	20.1%	10.2%	18.1%	2.3%	13.8%	3.7%	2.0%
Calibrated	30.1%	18.5%	8.5%	19.5%	4.2%	13.8%	3.7%	1.7%
				2006				
Historical real	29.8%	18.6%	8.4%	19.7%	3.0%	13.4%	5.3%	1.9%
Unadjusted	29.7%	21.3%	10.3%	17.1%	2.0%	13.4%	4.1%	2.1%
Calibrated	30.0%	19.4%	8.6%	19.5%	3.3%	13.4%	4.1%	1.7%

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Table 5. Average daily and hourly generation and abatement at different times.

	week day	weekend day	day	night
Generation	[TWh/day]		[GWh/h]	
2005	8.23	7.07	350	308
2006	8.27	7.21	352	312
CO_2 abatement	[kton/day]		[kton/h]	
2005	65.3	166.0	3.3	4.5
2006	37.4	89.7	2.1	2.3

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Table 6. Quarterly abatement and associated determinants, 2005 and 2006.

		2005				2006			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
average generation	[TWh/day]	8.7	7.4	7.4	8.2	8.8	7.5	7.4	8.2
average gas/coal price	[-]	2.6	2.1	2.1	5.2	4.8	2.5	2.3	2.0
average EUA price	[euro/ton]	9.0	18.4	23.2	21.9	26.1	19.0	15.9	9.4
abatement	[Mton]	3.4	12.6	16.0	3.5	0.7	6.2	6.9	5.3

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Table 7. Changes in inter-zonal power flows and associated CO_2 emission reduction effects in response to EUA prices, 2005-2006.

	2005		2006	
	TWh[a]	Mton[b]	TWh[a]	Mton[b]
France to Germany	+ 3.98	1.86	+ 1.64	0.75
France to Benelux	+ 0.50	0.18	+ 1.36	0.48
France to the UK	- 0.23	- 0.1	+ 0.85	0.39
Germany to Benelux	- 3.65	0.41	- 2.12	0.22
Poland to Germany	- 1.01	0.35	- 1.07	0.38
Poland to Central Europe	- 1.15	0.42	- 0.67	0.24
10 other flows		- 0.1		- 0.31
TOTAL		3.00		2.15

[a] A positive shift in this context means a higher flow in the historical EUA scenarios than in the zero EUA scenarios, a negative sign indicates the reverse.

[b] The emission reduction (= difference between emission in zero EUA case and emission in historical EUA case) is listed.