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# CO<sub>2</sub> Abatement from RES Injections in the German Electricity Sector: Does a CO<sub>2</sub> Price Help?<sup>1</sup>

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## Abstract:

The overlapping impact of the Emission Trading System (ETS) and renewable energy (RE) deployment targets creates a classic case of interaction effects. Whereas the price interaction is widely recognized and has been thoroughly discussed, the effect of an overlapping instrument on the abatement attributable to an instrument has gained little attention. This paper estimates the actual reduction in demand for European Union Allowances that has occurred due to RE deployment focusing on the German electricity sector, for the five years 2006 through 2010. Based on a unit commitment model we estimate that CO<sub>2</sub> emissions from the electricity sector are reduced by 33 to 57 Mtons, or 10% to 16% of what estimated emissions would have been without any RE policy. Furthermore, we find that the abatement attributable to RE injections is greater in the presence of an allowance price than otherwise. The same holds for the ETS effect in presence of RE injection. This interaction effect is consistently positive for the German electricity system, at least for these years, and on the order of 0.5% to 1.5% of emissions.

Key words: ETS, RE policy, interaction, emission abatement, Germany

JEL-code: L94, Q58

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# 1 Introduction

Through its climate and energy package, the EC aims for a sustainable, secure and competitive energy supply. In March 2007, the EU leaders defined the so called 20-20-20 targets by 2020, meaning a reduction of greenhouse gas emissions of 20% compared to 1990 levels, a 20% share of renewable energy in the overall energy consumption, and a 20% increase in energy efficiency compared to a projected baseline. The climate and energy package implementing these targets was agreed by the European Parliament and Council in December 2008 and entered into law in June 2009.

For electricity, these targets imply even larger reductions in emissions. CO<sub>2</sub> emissions from electricity generation and heavy industry are capped to a level of 21% below 2005 levels in 2020 by the European Union Emissions Trading System (EU ETS). While the distribution of the emission reductions required by the ETS cap between electricity and heavy industry can never be known exactly, modelling and expert opinion agree that abatement opportunities are cheaper and more plentiful in the electricity sector so that a greater reduction of emissions can be expected in that sector. Similarly, the cheapest opportunities for displacing conventional energy use by renewable energy sources exist in the electricity sector so that the renewable energy (RE) targets can be expected to reduce emissions in the electricity sector more than in other sectors of the economy (such as industry, households, transportation, or buildings).

The overlapping impact of the ETS and RE deployment targets creates a classic case of interaction effects. When emissions are capped, such as in a cap-and-trade system like the EU ETS, any external factor that affects emissions changes the demand for allowances and thereby the price of allowances. When the external factor is non-policy related, such as technological change, changes in expected rates of economic growth or in expected fuel prices, the resulting increase or decrease in the allowance price signals the greater or lesser need for abatement to achieve the unchanging cap in a least cost manner. However, when the external factor is directly attributable to policy, such as RE incentives, energy taxes, or nuclear energy, the outcome is more problematic. For instance, an energy tax for the purpose of financing transportation infrastructure or closing some fiscal deficit, will reduce energy demand somewhat and thereby CO<sub>2</sub> emissions and the demand for allowances. Nevertheless, the resulting lower allowance price remains an efficient adjustment to the achievement of some other policy objective that will also affect capped emissions. The same could be said for an independent policy objective that has the opposite effect, such as a phasing out of nuclear energy as a matter of safety or non-proliferation policy. Assuming the policy objective is justified and the instrument well chosen, the secondary effect on CO<sub>2</sub> emissions and the allowance price is part of the external environment, effectively no different than changes in world oil prices or in expected rates of economic growth.

A problem arises only when the policy objectives are the same, as is arguably the case for RE incentives. To the extent that the purpose of these incentives is to reduce CO<sub>2</sub> emissions as a matter of climate policy, and a cap is already in place to achieve this same objective, no additional reduction

occurs. If the incentive is such as to induce deployment of RE that would not be forthcoming in response to the CO<sub>2</sub> price, the effect is only to reduce the price of allowances and to substitute a more costly form of abatement for what the cap would have required in the absence of the RE incentives. The reduction in the allowance price is simply signalling the reduction in demand in one part of the ETS and the consequent need for less abatement in other parts of the capped system.

The object of this paper is to estimate the actual reduction in demand for European Union Allowances (EUAs) that has occurred due to RE deployment in one not inconsequential part of the EU ETS: the German electricity sector for the five years, 2006 through 2010. For now, we leave aside the related issue of the effect of this reduction in demand for EUAs on their prices as well as that of the cost of the CO<sub>2</sub> emissions reduced by RE deployment. We find that RE injections have reduced CO<sub>2</sub> emissions from the German electricity sector by 10% to 16% in these years. Somewhat surprisingly, we also find that the abatement attributable to RE injections is greater in the presence of an allowance price than otherwise. And, when we seek to determine the amount of emission reduction attributable to the EUA price in these years, we also find that the quantity of abatement is greater with RE injections than without.

The existence of this reinforcing effect of the overlapping instrument on abatement is not only surprising, but it has potentially significant policy implications concerning the one-policy-one-instrument rule. Much of the paper is devoted to analysing this unexpected interaction to determine its causes and to whether it is a general case or a more special one with limited applicability and policy implication.

In the remainder of the paper, section 2 provides a brief review of the literature concerning interaction effects when instruments overlap and the reduction of emissions that results from RE incentives. Section 3 describes the simulation model that has been used, together with the different scenarios and the model calibration to actual historical numbers. Section 4 presents the overall simulation results and section 5 focuses on understanding the observed interaction effect with respect to abatement. Section 6 concludes.

## **2 Literature Review**

The potential for a price interaction when instruments to promote RE deployment overlap with a cap-and-trade program is widely recognized and has been thoroughly discussed in the literature. In Europe, the early discussion was necessarily theoretical and included several articles proposing ways to coordinate the use of overlapping instruments in a way that would lead to more optimal results (Morthorst, 2001; Jensen and Skytte, 2003; Sorrell and Sijm, 2005; Skytte, 2006; Meran and Wittman, 2008). As the European 20-20-20 targets came to be formulated, attention turned to these specific proposals and how they would operate on existing systems. As an example, Abrell and Weigt (2008) simulated the interaction between the 20% CO<sub>2</sub> reduction target and the 20% RE share target in a computable general equilibrium model of the German economy based on 2004 data and found that

achievement of the 20% RE share target made the CO<sub>2</sub> reduction target superfluous and thereby reduced the EUA price to zero. De Jonghe et al. (2009) widened the scope of targets to include the full range of plausible CO<sub>2</sub> emission reduction and RE deployment targets in a simulation of the interconnected electricity systems of Germany, Benelux, and France. They similarly found that RE share targets could reduce the allowance price to zero depending on the stringency of the two targets and thereby defined a zero-price frontier. Like Abrell and Weigt (2008), they found that a 20% RE quota rendered a 20% CO<sub>2</sub> emission reduction redundant (although not more stringent CO<sub>2</sub> emission reductions targets). All of this literature focuses on the price interactions resulting from overlapping instruments. None have identified the interaction in abatement.

In estimating the emission reduction due to RE injections, the above studies calculate CO<sub>2</sub> emission reductions as the difference in carbon content of the fuel substitution that takes place as a result of the RE injections. This is a straight-forward way to calculate emission reductions; yet, there is another literature that argues, especially for wind energy injections into the electricity grid, that the combination of intermittency and reduced utilization leads to decreased efficiency in the operation of fossil-generating plants and therefore to a smaller reduction of emissions than suggested by estimates that ignore these power system dynamics (Denny and O'Malley, 2006; Denny and O'Malley, 2007). Lang (2009) has even gone so far as to argue that the fuel inefficiencies created by intermittent injections in integrated electricity grids result in negligible if any net reductions of emissions.

Such questions about the actual reduction of emissions resulting from RE injections have led to several ex post evaluations in the U.S. of observed emissions reductions for CO<sub>2</sub>, SO<sub>2</sub> and NO<sub>x</sub> corresponding to actual wind injections based on hourly emission data and hourly wind data (Novan, 2011; Kaffine *et al.*, 2011; Cullen, 2011).<sup>5</sup> These US studies are noteworthy in being able to use hourly variations in emissions corresponding to hourly variations in wind energy injections and thereby to observe actual system-wide results without having to make assumptions about changes in fossil-fired power-plant efficiencies resulting from intermittent operation or other grid-imposed constraints. These studies provide no support to the arguments presented in Lang (2009) for they find significant emissions reductions associated with RE injections, although they do find that the reductions are less than what would be suggested by estimates based on average emission rates. In particular, they emphasize that the reductions vary considerably according to the pre-existing configuration of generation capacity and its dispatch in meeting load. For instance, Kaffine et al. (2011) find that while wind injections in the coal-dependent Upper Midwest reduce CO<sub>2</sub> emissions by 0.92 t-CO<sub>2</sub>/MWh, the reduction drops to 0.29 t-CO<sub>2</sub>/MWh in gas-dependent California and to 0.52 t-CO<sub>2</sub>/MWh in the more mixed coal and gas system in Texas. Focusing on Texas and using different years and estimation techniques, Novan (2011) and Cullen (2011) find an average CO<sub>2</sub> reduction per MWh is approximately 0.67 t-CO<sub>2</sub>/MWh and 0.75 t-CO<sub>2</sub>/MWh, respectively.

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<sup>5</sup> The emissions data are from the Continuous Emissions Monitoring System reports that all generating plants in the US are required to make to the US EPA and which are publically available. Wind injection data is from electricity network operators as is the case in Europe.

The absence of hourly CO2 emissions data in Europe does not allow for comparable estimates that are free from counterfactual assumptions about system operations. Consequently, analysts must rely on calibrated model simulations that combine the use of data concerning actual generating capacity, load requirements, RE injections, fuel and CO2 prices and other data affecting observed dispatch with counterfactual assumptions about system operation in the absence of those injections. Our paper adopts such an approach in seeking to determine the extent to which RE injections in the German electricity system reduced CO2 emissions (and therefore demand for allowances) from 2006 through 2010. In the interest of comparing the relative effectiveness of observed EUA prices and RE incentives in reducing CO2 emissions, we also estimate the CO2 emission reductions attributable to actual EUA prices both in the presence of RE injections and in the absence of those injections. Other papers have estimated CO2 emission reductions in the electricity sector as a result of the EU ETS (Delarue *et al.*, 2010a; Ellerman and McGuinness, 2008), but these papers took RE injections as given and therefore failed to detect the interaction in abatement that we find in the simulations presented below. To the best of our knowledge, this is the first paper to identify this interaction in abatement when ETS and RE policies overlap, as well as the first to estimate the reduction in CO2 emissions in a European country resulting from RE injections from a strictly ex post perspective.

### 3 Simulation model set up

The analysis is based on a deterministic unit commitment model of the German electricity market covering the time range from 2006 till 2010 on an hourly time frame calibrated to observed market outcomes. The general model description is provided in the following section. The adjustments for the German market representation and underlying dataset are described afterwards.

#### 3.1 Model description

The model is formulated as linear mixed integer program including a binary online variable and a start-up variable (see Abrell *et al.* 2008, for details). The model minimizes total generation costs including start-up costs given a fixed hourly demand level:

$$\min_{g_{p,t} \geq 0} \text{cost} = \sum_{p,t} mc_{p,t} g_{p,t} + \sum_{p,t} sc_p g_p^{\max} up_{p,t} \quad \text{objective} \quad (1)$$

$$\sum_p g_{p,t} + PSP_t^{\text{down}} = d_t + PSP_t^{\text{up}} \quad \forall t \in T \quad \text{energy balance} \quad (2)$$

$$on_{p,t} g_p^{\min} \leq g_{p,t} \leq on_{p,t} g_p^{\max} \quad \forall t \in T, p \in P \quad \text{capacity constraint} \quad (3)$$

$$up_{p,t} \geq on_{p,t} - on_{p,t-1} \quad \forall t \in T, p \in P$$

$$on_{p,t-1} - on_{p,t} \leq 1 - \sum_{\tau=t}^{t+sd_p} up_{p,\tau} \quad \forall t \in T, p \in P \quad \text{start-up constraints} \quad (4)$$

$$PSP_{t+1} = PSP_t - PSP_t^{down} + \eta_{PSP} PSP_t^{up} \quad \forall t \in T \quad \text{PSP balance} \quad (5)$$

$$\begin{aligned} PSP_t^{up} &\leq PSP^{up\_max} & \forall t \in T \\ PSP_t^{down} &\leq \min[PSP^{down\_max}, PSP_t] & \forall t \in T \end{aligned} \quad \text{PSP capacity constraints} \quad (6)$$

The model objective (equation 1) is to minimize total supply costs (*cost*) consisting of the two components generation costs and start-up costs. Total generation costs are given by marginal generation costs (*mc*) and hourly generation (*g*) for each plant  $p \in P$  and hour  $t \in T$ . Start-up costs are added as a cost block based on the plant specific start-up costs (*sc*) and the installed plant capacity ( $g^{max}$ ) in the hour of start-up defined by a binary start-up variable (*up*).

This cost objective is subject to technical constraints. The energy balance (equation 2) ensures that the total generation of all plants and pumped storage generation ( $PSP^{down}$ ) equals the given demand (*d*) and pump storage demand ( $PSP^{up}$ ) in each hour. To avoid infeasibilities of the model in case that the existing plant capacities are insufficient to cover demand a generic plant has been added with high marginal costs and no capacity limit. This can be interpreted as a form of lost load.

The capacity constraint (equation 3) ensures that if a plant is online (binary variable *on* is 1) the actual generation has to be within the minimum ( $g^{min}$ ) and maximum ( $g^{max}$ ) capacity limits. If the plant is offline (binary variable *on* is 0) the generation is fixed to 0. The plant's unit commitment is restricted by start-up constraints (equation 4). The first constraint ensures that if a plant switches from offline to online in period  $t$  ( $on_{t-1}=0, on_t=1$ ) the start-up variable (*up*) takes the value of 1 in the hour of start-up. The second constraint limits the possibility to restart a plant if has been shut down in period  $t$  ( $on_{t-1}=1, on_t=0$ ) for the shut-down time frame *sd*. We do not consider externally defined minimum run-time restrictions as we assume that all plants can technically be shut down after one hour of operation.

The model includes an endogenous pumped storage representation. The pumped storage balance (equation 5) defines the next period's storage level ( $PSP_{t+1}$ ) as the current storage level ( $PSP_t$ ) plus the ingoing pumped storage demand ( $PSP^{up}$ ) assuming an efficiency level ( $\eta_{PSP}$ ) minus the outgoing pumped storage generation ( $PSP^{down}$ ). In- and outgoing flows are restricted by the available capacities (equation 6): in case of demand the restriction is the installed storage capacity ( $PSP^{up\_max}$ ), in case of generation the restriction is the installed turbine capacity ( $PSP^{down\_max}$ ) or the storage level ( $PSP_t$ ) whichever is lower. There is no upper bound on the PSP storage level.

The model is formulated as a mixed integer linear program in the General Algebraic Modeling System (GAMS; Brook et al., 2008) and solved using the CPLEX solver. All parameters are externally provided and deterministic (see next section) and the model is solved with hourly time steps. As the full 8760 hours of a year are not solvable within one model run each year is divided in monthly blocks. The pumped storage is assumed to be empty in the first period of each month, each plant is initially offline, and no linkage between the monthly blocks is included (i.e. storage levels or plant status).

Perfect foresight of load and wind injections is assumed in scheduling the dispatch of available plants. Although this might seem an inappropriate treatment of intermittency, Denny and O'Malley (2006) found that in Ireland the error in CO<sub>2</sub> emissions due to deviations from expected wind forecasts was less than 1%.

### 3.2 Input data

The dataset for the generation system is based on VGE (2005, 2006, 2009) and Umweltbundesamt (2011) and extended using company reports and includes all conventional facilities in Germany with more than 100 MW generation capacity by plant and fuel types. The total plant capacity has been cross-checked with aggregated numbers presented in Eurelectric (2010) and the divergence due to missing small power plants (< 100MW) has been added in form of average plant blocks of the respective type.

Marginal generation costs ( $mc$ ) of each plant are based on fuel and emission costs accounting for the plants efficiency. Plant efficiency is estimated using the construction or retro-fitting year as proxy following Schröter (2004) penalizing older plants with lower efficiency and consequently higher generation costs and emission levels. The efficiency value is assumed to be constant over the output range of a plant thus neglecting potential efficiency losses due to lower utilization in presence of RE injection. Fuel prices for oil, gas, and coal are taken from the Federal Office of Economics and Export Control (BAFA) and vary for each month. CO<sub>2</sub> emissions are based on the carbon content of the different fuels (IPPC, 2006) and the plant efficiency. Emission Allowance (EUA) prices are the average monthly price from the European Energy Exchange (EEX).

Start-up costs and shut-down times are taken from Dena (2005) and Schröter (2004). Gas turbines are assumed to have no start-up restrictions while coal and lignite fired steam plants have several hours downtime. The plants maximum generation capacity ( $g^{max}$ ) is adjusted for each month via seasonal availability factors based on Hoster (1996). Combined heat and power plants (CHPs) are provided with an average load profile varying for each month which they have to follow within the boundary of  $\pm 10\%$ . The generic plant needed to cover lost load cases has marginal costs based on gas or oil prices (whichever is higher), an efficiency value of 30%, an emission factor of 0.3 t/MWh and a cost markup of 25 €/MWh.

Demand ( $d$ ) represents the residual demand levels accounting for import and export as well as RE injection. The underlying hourly demand is based on ENTSO-E (2011). As hourly values and aggregated numbers on yearly level provided by ENTSO-E do not match, the hourly levels have been scaled to match the aggregated values (see also model calibration in the next sub section). Furthermore, the German demand has been adjusted to account for cross border exchanges as provided by the network operators for 2006 till 2008 and ENTSO-E for 2009 and 2010. From the residual demand renewable energy injection has been deducted. Hourly wind input is provided by the four network operators for the full time frame. Hourly solar and biomass injections are not available for the full time frame. Based on the hourly injection levels provided for the East German region by the TSO

50Hertz Transmission, an average monthly profile has been generated providing actual energy input based on the installed capacity. Consequently the model accounts for the high variability of wind injection but not for solar variations. Biomass is running with a relative constant profile.

### 3.3 Model calibration

To present a realistic outcome, the model needs to be calibrated to historical conditions. The calibration focuses on reproducing the observed yearly generation by fuel via adjusting the marginal generation costs of coal and gas plants and adjusting the availability factors. If the model is run without calibration to observed operations, the use of coal tends to be too high compared to gas-fired generation. This seems to be a general result in simulating the operation of the European electricity system. As shown in Delarue *et al.* (2010a), failure to correct for real world departures from the model's assumed theoretical optimum can lead to significant errors in estimating residual quantities, such as abatement. For instance, if more unutilized gas-fired capacity is assumed available for fuel switching than is the case in actuality, abatement estimates will err on the up-side.

To overcome these potential errors, the model is calibrated as follows. First the hourly demand level is scaled to match the peak and aggregated values as reported by Eurelectric (2010). Note that the sum of the hourly ENTSO-E numbers already miss about 10% of the aggregated number reported by ENTSO-E (which on its turn is lower than the Eurelectric aggregate).

Second, plant availability and generation costs are adjusted to match the modeled yearly generation output with the observed output clustered by fuel. A single focus of the calibration to plant availability is not feasible as this severely restricts the generation options once RE injection is withdrawn.<sup>6</sup> The seasonal availability therefore is limited to be reduced by no more than ten percentage points which mainly affects coal plants. Lignite and nuclear plants typically needed a slight increase of their seasonal availability to match observed output. In addition costs markups for coal plants are included that are within the range of 10 to 20 €/MWh whereas gas and oil plants have little to no additional markups. These markups are only applied during peak hours (8am-8pm on working days) whereas during off-peak hours coal units have either no or slightly negative markups. This coal penalty is adjusted to provide a reasonable match of modeled and observed output.

These restrictions are kept in place in all the alternative scenarios as described below, which raises the question of whether these corrections are related to the presence of a carbon price or RE injections. Delarue *et al.* (2010a) found that the calibrated model based on the European electricity system for 2003-04 (when there was no carbon price and RE injections were less) also performed better in 2005 and 2006 when a carbon price was present and RE injections were greater. Still, it is possible that, in a setting without RE injection, coal plant availability would be greater than is assumed

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<sup>6</sup> First model runs show that coal capacities would have to be reduced by up to 40% of their installed capacities to provide reasonable output levels.

in the calibrated runs. If so, our estimates of abatement from RE injections would likely be understated: more coal and less gas generation would be used in the absence of RE injections.

### **3.4 Scenario outline**

Simulations are performed on a yearly level, with time steps of 1 hour. The considered years are 2006, 2007, 2008, 2009 and 2010. Counterfactual simulations are made based on the simulation that is calibrated to actual conditions in these years. Focus throughout these analyses is on the impact of the ETS and of RES injections on CO<sub>2</sub> emissions.

#### **3.4.1 RES – ETS impact on CO<sub>2</sub> emissions and marginal generating cost**

The above described model setting is used to derive four basic scenarios:

1. *OBS*: This observed case represents the calibrated model equivalent of the actual market outcomes. The EUA prices are provided as an external cost parameter increasing the marginal costs (*mc*) of each power plant based on the emission intensity of the fuel and the plant efficiency. Injection from renewable sources<sup>7</sup> is deducted from the demand as described above.
2. *RES*: This case reflects only the actual RE injections with EUA prices fixed at zero representing a setting without the ETS in place.
3. *ETS*: In this case the RE injection is fixed at zero whereas the EUA price is kept at the observed price level without adjustment for the removal of the RE injections.
4. *NOPOL*: This case represents the no-policy counterfactual where both the EUA price and the RE injection are fixed at zero thereby simulating conditions when neither an ETS nor an RE policy is in place.

Those basic scenarios allow an evaluation of the merit order effect (i.e., the effect on marginal generating cost) of RES and ETS, the emission abatement by the ETS and by RE injection, and possible interactions of those two elements.

#### **3.4.2 Impact of different types of RES**

In a second analysis step, we distinguish between three different types of renewable injection to analyze the contributions of each given their differing quantities and injection patterns. Most of our discussion treats all three together as “RE injections” but this second step of the analysis is intended to identify the extent to which the abatement effects of each type are different. Data on hourly injections of generation from wind are available, but not the data for biomass and solar so that injections have to be based on average patterns. Solar is modeled with a monthly average daily injection profile with a peak in the midday hours. Each day within a month therefore follows the same pattern in each of the

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<sup>7</sup> We refer to wind, biomass and solar energy as renewable energies whereas hydro generation is classified as conventional.

observed years, only varied by the installed capacity and thus total output. Biomass is modeled with a base load profile and thus replaces similar fossil quantities during peak and off-peak periods.

### 3.4.3 Estimating Displaced Abatement

In a final step we provide estimates for the price interaction of RE injection and EUA prices. As noted previously, if RE injections occur within a cap-and-trade system, CO<sub>2</sub> emissions are not reduced in the aggregate and the main effect is to displace abatement that would have occurred elsewhere in the system. One measure of this displacement would be the abatement attributed to RE injections; however this estimate would be accurate only if the reduction in allowance demand had no effect on the allowance price. So far we use the observed allowance price in modeling the effect of a carbon price both where RE injections are present (OBS case) and when they are not (ETS case), thereby effectively treating the observed EUA price as an exogenously determined, variable tax that is not affected by the actual level of emissions. In the absence of a model of the price response within the ETS as a whole to German RE injections, adjustment of the EUA price for the ETS-only case would be speculative.

However, we can estimate the extent to which higher EUA prices would induce greater fuel switching in the German electricity sector and thereby reduce the amount of displaced abatement outside of that sector. To do so, the basic model is adjusted for those sensitivity tests by introducing an emission cap constraint for each year:

$$\sum_{p,t} emf_p g_{p,t} \leq emcap \quad \text{emission cap} \quad (7)$$

Consequently the total amount of emissions, given by the plant individual emission factor (*emf*) and the hourly plant output (*g*), has to remain within that year's emission limit (*emcap*) as simulated in the Observed Case.<sup>8</sup> The externally defined EUA price is neglected in this model as the price will be endogenously defined as dual on the emission constraint (*equation 7*).<sup>9</sup> If the RES injection is reduced the model will increase fossil-fired generation and switch from coal to gas/oil fired generation to keep emissions within the cap. However, since only the German electricity system is regarded in this setting, the fuel switching possibilities are limited and the model becomes infeasible if the abatement due to RES injection cannot be compensated. To avoid this problem an external abatement option (*ext*) has been included to indicate the amount of abatement displaced to other parts of the ETS.

$$\sum_{p,t} emf_p g_{p,t} + ext \leq emcap \quad \text{emission cap} \quad (8)$$

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<sup>8</sup> As the model only includes the German electricity sector so does the estimated emission cap also only reflect emissions in this sector. Furthermore the model is run with monthly segments and consequently the annual cap is implemented as monthly limit, preventing seasonal emission shifts within a year.

<sup>9</sup> The model methodology has been tested by reproducing the observed EUA prices with the endogenous emission cap. If the RE injection is kept in place the resulting endogenous emission price is equivalent to the EUA prices that were used to determine the emission cap.

This external abatement option is included with a penalty cost ( $c^{pen}$ ) that can be interpreted as the price that the German electricity sector would pay in the absence of the RE injections. Three different levels are assumed (50/100/150 €/t)<sup>10</sup> and the objective function is adjusted accordingly:

$$\min_{g_{p,t} \geq 0} cost = \sum_{p,t} mc_{p,t} g_{p,t} + \sum_{p,t} sc_p g_p^{max} up_{p,t} + c^{pen} ext \quad \text{adjusted objective} \quad (9)$$

The simulations allow an approximated estimation of how much the displaced abatement would be reduced by increased fuel substitution in the German electricity system in response to higher EUA prices resulting from removing German RE injections from the same electrical system.

## 4 Result Overview

The simulation results of the different scenarios will be discussed and the main trends and insights are presented, for the three sets of simulations. A detailed numerical overview of the results is provided in the Appendix.

### 4.1 RES - ETS impact on CO2 emissions

The panels in Figure 1 and Figure 2 present various effects of the two instruments when used jointly and alone by scenario and year. Panel a of Figure 1 shows the total emission for the four scenarios over the observation period. It is evident that in the cases where RE injection is not in place (ETS and NOPOL) the total emissions are significantly higher. Based on those emission values it is possible to estimate the abatement attributable to each instrument when it is acting alone and in conjunction with the other instrument. This can be done by using the OBS or the NOPOL case as starting point, i.e. for the impact of the EU ETS the comparison of the ETS and NOPOL case provides the emission impact of the ETS with no RE injection, while comparing the OBS and RES case provides the ETS impact with RE injection in place. Panel b of Figure 1 provides the estimates for both the ETS and RES impact on total emissions.<sup>11</sup>

Two features stand out. First, as implemented in Germany, RES policy is much more effective in reducing CO2 emissions within the German electricity sector than the EU ETS. The emission impact of the EUA price is in the range of 1 to 3% compared to an 11 to 19% impact of RES generation. Second, the abatement attributable to each is greater when that instrument is deployed in conjunction with the other. Alternatively, when employed together, the abatement is greater than the sum of the individual abatement effects when each instrument is deployed individually. This reflects the reinforcing interaction effect that we have already noted and which will be discussed extensively in the next section of the paper.

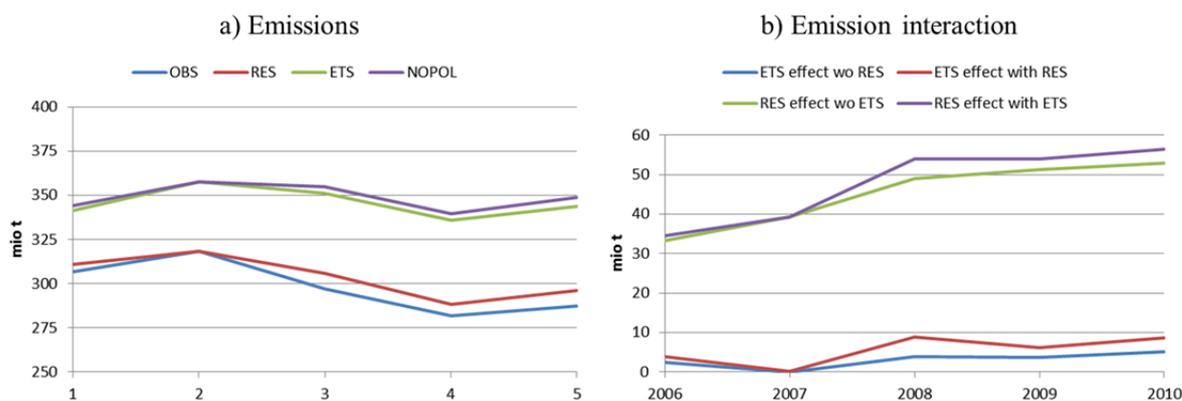
<sup>10</sup> If the external abatement option is used, and hence an external penalty is incurred, the model setting is identical to a system without the cap on emissions but with an exogenously imposed fixed CO2 price, equal to the penalty.

<sup>11</sup> Note that we refer to the total RE injection (wind, solar PV and biomass) as being the impact of RE policy within the analysis. This is a simplification as is explained in section 4.3.

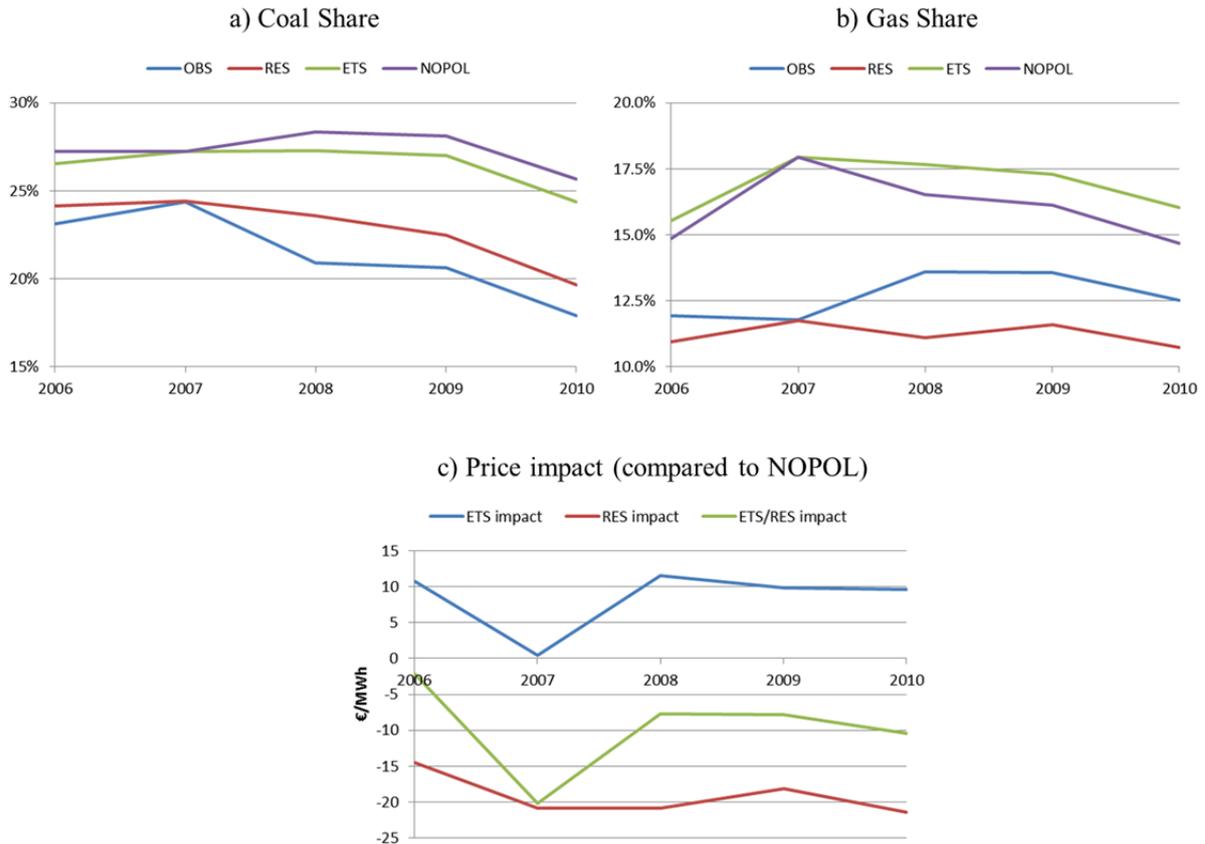
Panels a and b of Figure 2 show coal and natural gas shares of generation, respectively. RE injections decrease the shares of generation by coal and natural gas by 3 to 6 percentage points and 4 to 6 percentage points, respectively, depending on the year. The addition of a carbon price reduces the coal share of generation by another 1 to 3 percentage points (except in 2007 when the carbon price was effectively zero), but raises the share of gas by an approximately equal amount. These changes in the fuel shares are directionally what would be expected and they illustrate again that the RE incentives in Germany have a much greater effect than the EU-wide carbon price. However, unlike the carbon price, the RE policy does not discriminate according to the carbon content of fuels and falls about equally on coal and natural gas. The carbon price compensates gas generation somewhat, but not the full amount lost due to RE injections. Note also that the ETS price has a greater compensating effect when the RE injections have been made than when there are none.

Finally, panel c of Figure 2 shows the effects of the instruments on marginal generating cost. As with the fuel shares, these effects are what would be predicted directionally. The EUA price acting alone would have increased marginal generating cost by around 10 euros per MWh (again except in 2007), while the merit order effect of the RE injections when taken alone would reduce these costs by from 12 to 20 euros per MWh. When both operate together as in the observed case, the net effect is a decrease of from 3 to 10 euros per MWh depending on the year. While the carbon price increases the cost of marginal generation, the displacement of that marginal generation by RE injections more than compensates.

**Figure 1: Emission impact**



**Figure 2: Quantity and price impact**



Other aspects of system performance are as might be expected. Start-up costs are higher in the cases without RES injection reflecting the need for more plants to cover demand.<sup>12</sup> However, the share of start-up costs compared to fuel and emission costs is less than 2%. The usage of pumped storage varies over the years and shows no clear trend in relation to RES or ETS policy. Since the model does not include an endogenous import/export calculation, changes in the European trade balances cannot be estimated. Finally the lost load values are less than 0.5% of total generation which shows that the conventional German generation capacities are on average sufficient to replace the installed RE capacities.

Table 1 provides the annual RE injections, the abatement attributable to those injections with and without the interaction effect (IA) and the resulting average emissions reduction per MWh of injected RE. CO<sub>2</sub> abatement and the average intensity of the generation displaced by RE injections vary depending on whether the interaction term is included, that is, whether the ETS CO<sub>2</sub> price observed in these years is present, as also illustrated in Figure 1. These statistics are respectively the

<sup>12</sup> Test cases with different injection profiles for wind (base load band, average daily profile, and hourly varying injection) did not result in significant changes of the start-up costs. The hourly structure of the model and its deterministic setting limit evaluations of the impact of RES intermittency on the results (perfect foresight has an important impact on the use of the pumped storage).

sums and averages of the carbon intensity of the fuels combusted in the generation backed off by the RE injections.<sup>13</sup>

As can be seen, the average CO<sub>2</sub> intensity abated varies considerably from year to year depending on the hourly interaction of load and RE injections and the ordering of dispatch as fuel prices vary (monthly in the model). When the 2007 observation for average abatement intensity is removed from the w/ IA column due to the non-existent CO<sub>2</sub> price in that year, the annual variation is 10% when the CO<sub>2</sub> price is present and about 15% when there is no carbon price (2007 is now included in the sample). These statistics are similar to those found by Novan (2011) and Kaffine *et al.* (2011) for CO<sub>2</sub> abatement due to wind injections in Texas, which has a mixed configuration of coal and gas-fired power plants like that in Germany.

Table 3 and Table 4 in appendix provide additional numerical results of the simulations.

**Table 1: RE injections, CO<sub>2</sub> abatement, and average abatement intensity**

Year	RE Injection (TWh)	CO <sub>2</sub> Abatement (Mt-CO <sub>2</sub> )		Average Intensity (t-CO <sub>2</sub> /MWh)	
		w/ IA	w/o IA	w/ IA	w/o IA
2006	50.3	34.5	33.2	0.68	0.66
2007	64.0	39.3	39.3	0.61	0.61
2008	71.3	54.0	49.0	0.75	0.69
2009	73.6	53.9	51.3	0.73	0.70
2010	79.1	56.5	53.0	0.71	0.67

## 4.2 Impact of different types of RES

In a next step the impact of the three renewable energies wind, solar and biomass is examined in more detail. In the observation period (2006 till 2010), the capacity of all types of RE increased: installed wind capacities grew from 18 to 27 GW, biomass from 3.2 to 6.4 GW, and solar from 2 to 17 GW. The impact of each form of RE injection on emissions and marginal generating cost is shown in the three panels of Figure 3, as well as that for all RE injections combined.

Panel a shows the injections for the three types of RE and the total. Solar and biomass are steadily increasing over this five-year period, while wind injections reach a peak in 2007-2008 and decline slightly thereafter. Wind injections constitute 60% of total RE injections in 2006, but by 2010 that share has fallen to 45%. In contrast, solar generation rises from 4% of aggregate RE injections in 2006 to nearly 13% in 2010 and the biomass share increases from 36% to 43% over the same period.

The emissions impact of these injections (panel b) follows the same general pattern but there are noticeable annual variations in the annual intensity of abatement. For instance, abatement from wind injections increases by 25% from 2007 to 2008 when these injections increase by only 2%. As will be explained in the next section, this significantly greater abatement from approximately equal

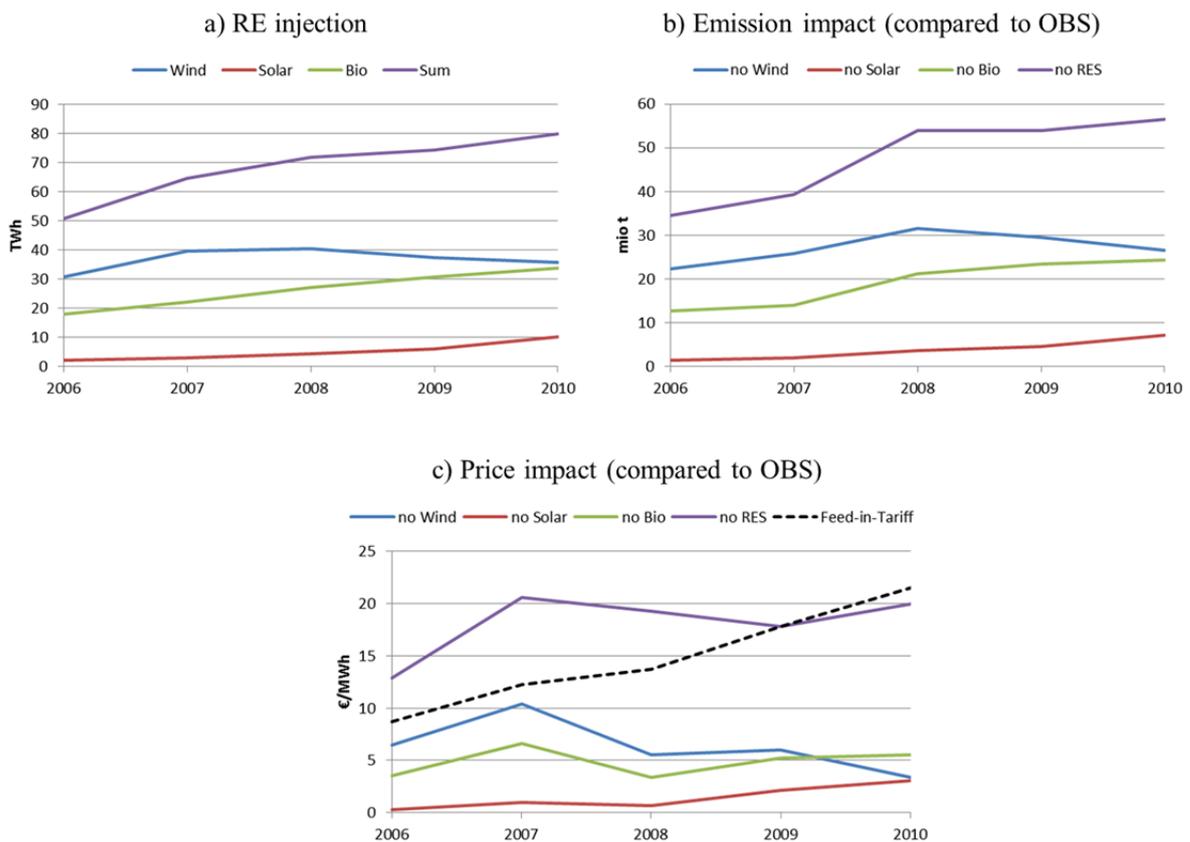
<sup>13</sup> The plant-specific intensity varies by fuel and plant efficiency: coal-fired power plants in the model have an average carbon intensity of 0.90 t-CO<sub>2</sub>/MWh and gas-fired plants one of 0.46 t-CO<sub>2</sub>/MWh.

annual wind injections is probably attributable to the significant difference in the CO<sub>2</sub> price between these two years.

The same change in the CO<sub>2</sub> price also likely explains the declining merit order effect of biomass and wind injections that is shown in panel c. In this panel, the merit order effect is shown in reverse, as the increase in marginal operating cost when the particular form of RE is withdrawn from the OBS scenario. Although the biomass capacities are higher in 2008-2010, the cost impact is highest in 2007. The reason is that a significant CO<sub>2</sub> price in 2008-10 leads to greater convergence of coal and gas based electricity costs leading to a less steep increase (decrease) in marginal operating cost as load increases (decreases). If the CO<sub>2</sub> price is zero or low, as in 2007, there is a larger gap between coal and gas based generation costs so that marginal operating cost tends to rise or fall more rapidly with variations in load.

For the sake of completeness, Table 5 in appendix provides additional numerical results for the different considered cases.

**Figure 3: Quantity, emission and price impact of RE**



### 4.3 The Redistribution of Abatement Due to RE Injections

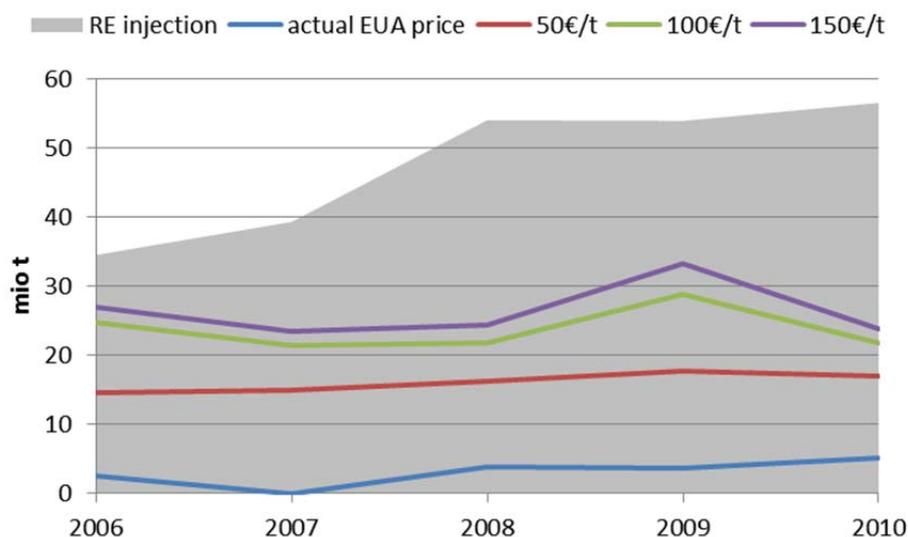
As we noted initially, the emissions impact of RE injections in a cap-and-trade system is not to reduce emissions, but only to reduce the allowance price and to change the geographic and sectorial

pattern of abatement. Our estimates of the annual reductions in allowance demand due to RE injections are accurate (within the limits of the model), but they do not reflect the redistribution of abatement between the German electricity sector and other parts of the EU ETS (the electricity sector outside of Germany and all of the industrial sector including that in Germany). To obtain an accurate estimate of displaced or reduced abatement in other parts of the EU ETS, account must be taken of the fuel switching that would occur within the German electricity sector in response to an EUA price that would be higher than the fixed, observed EUA price that we use in our ETS simulations, that is, when RE injections that contributed to the observed EUA price are not present.

Figure 4 shows the amount of abatement due to fuel switching in the German electricity sector under different EUA price assumptions (the four lines), as well as the emission abatement due to RE injection for comparison (the shaded area). The bottom line is the same as that in Figure 1(a) for the ETS effect without RES at the EUA price that is assumed unchanged despite the absence of RE injections. The three other lines show the same type of abatement but at arbitrarily higher EUA prices of €50, €100, and €150. The distances between these lines for any given year indicate the abatement from fuel switching that is either suppressed or encouraged as the EUA price falls or rises. To take 2008 as an example, RE injections of 72 TWh are shown to reduce demand for CO<sub>2</sub> allowances by 54 million tons including the interaction effect. If the increase in the demand for allowances in the absence of those RE injections were to increase the ETS-wide price to €50, increased fuel switching within the German electricity sector would reduce the redistribution of abatement outside of the sector by about 12 tons, or 22%. Equivalently, if German RE injections have suppressed allowance prices from €50 to about €15, 54 million tons of cheaper abatement have been displaced, including 12 million tons of abatement from fuel switching within the German electricity sector.

Finally, we do not model the extent to which higher carbon prices would elicit greater RE development, not only in Germany, but particularly elsewhere in other member states that do not provide comparable incentives for the development of renewable energy sources. For example, the German feed-in tariff for wind energy has been about 90€/MWh in 2006 while the wholesale electricity price has been about 50€/MWh. The difference of 40€ is a premium for wind energy, which is equivalent to an advantage created by a theoretic carbon price of about €45/ton-CO<sub>2</sub> for displaced coal generation (and about €37/ton for displaced gas generation). While this advantage is not as certain as that provided by a fixed feed-in tariff, it would not be unreasonable to suppose that a CO<sub>2</sub> price of €50 would induce some investment in wind. And, while it may be debated whether a €50 EUA price added to an expected electricity price would induce as much investment in wind capacity throughout the EU ETS as a guaranteed €90 price for wind-generated electricity has in Germany, a CO<sub>2</sub> price of €100 or €150 surely would.

**Figure 4: Abatement in Germany due to RE injection and fuel switching**

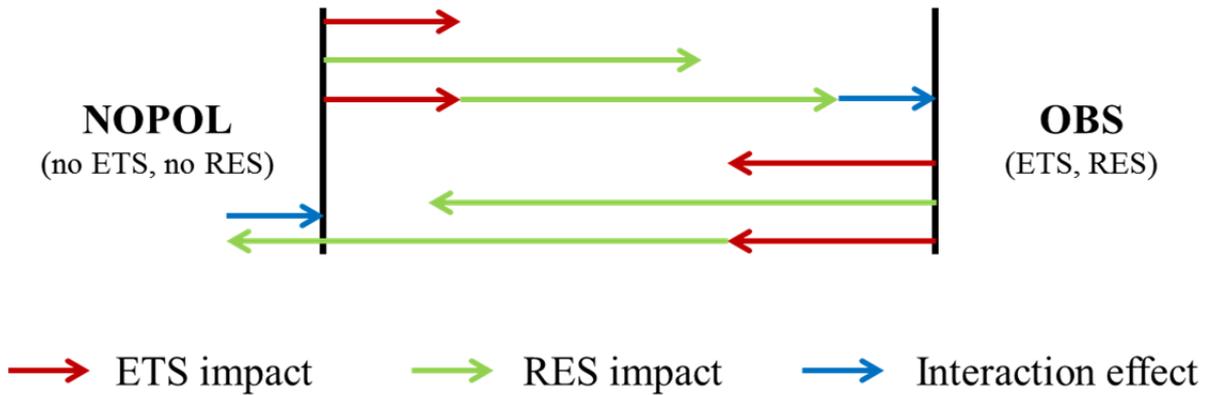


## 5 The Interaction Effect on Abatement

A salient feature of the results obtained in the above simulations is that for all years the abatement resulting from the use of both instruments together is greater than the sum of the abatement resulting from using either instrument alone. If generalizable, this result has significant policy implications. No longer would it be the case that overlapping instruments are either superfluous or redistributive only. There would exist an additional element, of uncertain importance, that should enter into policy deliberations.

Figure 5 illustrates this interaction effect. The top three lines portray the effect of adding RES or ETS to the NOPOL case. When deployed individually, each instrument has the effect noted, but when deployed together the total emission reduction is greater than the sum of the two by the length of the blue arrow, which we term the interaction effect. When moving from the opposite starting point, OBS, that is, withdrawing an instrument while leaving the other in place, the indicated effect for each individual instrument is greater than the corresponding line in the top panel. However, when both instruments are removed, the model returns to the no-policy position (as it must for any such model) and the total emission increase is less than the indicated sum of the parts by the amount of the interaction effect (blue arrow) found in the top panel. In effect, when either instrument is withdrawn from the case in which both policy instruments are in use (OBS), the indicated effect is larger than when the same instrument is added to the no-policy case (NOPOL) because removing either instrument from a situation in which both are present also removes the potential for interaction. Accordingly, if the individual effects of removing each instrument are summed to reflect the removal of both, one of the interaction terms must be subtracted.

**Figure 5: Observed interaction dependence**



### 5.1 Illustrating individual and interaction effects with the help of a methodological stacking model

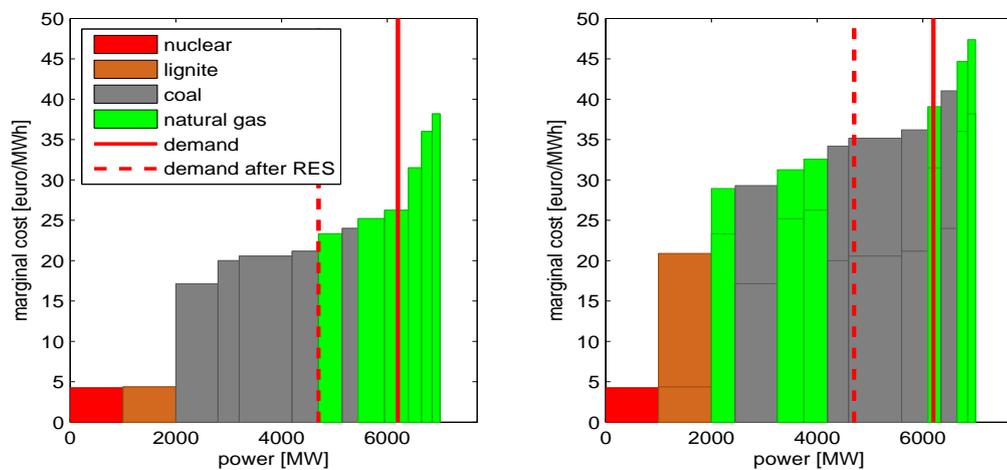
A simple stacking diagram of a methodological power system (meant here to reflect a mixed fuel system like Germany) can be used to explain these effects. The two panels of Figure 6 show a typical stacking order for a system with the following plants: one nuclear plant, one lignite plant, 5 coal fired power plants (varying in size and efficiency) and 6 gas fired power plants (also varying in size and efficiency). The panel on the left reflects the merit order with no carbon price, while that on the right reflects the merit order with a €15/ton CO<sub>2</sub> price. On the right-hand side panel, the marginal generating cost for each segment consists of the fuel cost (bottom part, identical to the LHS panel) and the emission cost (upper part, which is higher for carbon intensive fuels like coal and lignite). The solid red line on each panel reflects load in a particular hour without any RE injections, while the dashed line shows the net demand after RE injections of 1500 MW in that hour for each of these two cases (with and without a carbon price).

The different merit orders shown in each panel and the two red lines illustrate the four simulated scenarios performed in this paper on the German electricity system. A carbon price changes the dispatch order moving gas-fired plants lower down in the merit order and moving coal plants up. As can be readily seen in comparing the dotted red line with the solid one in each panel, injecting 1500 MW of RE sources displaces mostly gas when the CO<sub>2</sub> price is zero and mostly coal when the €15 CO<sub>2</sub> price is present. Thus in this example, abatement from an identical RE injection is greater when the carbon price is present.

Measuring abatement due to introducing a €15 CO<sub>2</sub> price is a little more complicated in that it depends on the amount of lower emitting capacity moved out of reserve and into active use to displace higher emitting capacity. In the example and focusing on the case with no RE injection (solid red line), introducing the €15 carbon price reorders the dispatch priority as before, but the coal plants that are moved closer to the operating margin are still needed to meet load. Consequently, as concerns these plants, there is no change in emissions. Emissions are reduced only when a gas plant that would be

held in reserve in the absence of the carbon price replaces a coal unit that would otherwise be in operation. In the illustration, one coal plant is moved into reserve and replaced by an equivalent amount of gas capacity moved from reserve into active generation, thereby achieving a modest reduction in emissions. However, if the 1500 MW RE injection is assumed, the net demand is reduced to the dashed red line. In this case, the ETS price causes a significant switch in the generation situated at the LHS of this net demand level, i.e., the generation used to meet this demand. Two coal are now placed into reserve and replaced by gas plants. Again, the effect of the ETS instrument is greater when used in conjunction with the RE instrument than when used alone.

**Figure 6: Merit order of the methodological system, 1500 MW of RES injection and CO2 price of zero (LHS figure) and 15 €/ton (RHS)**

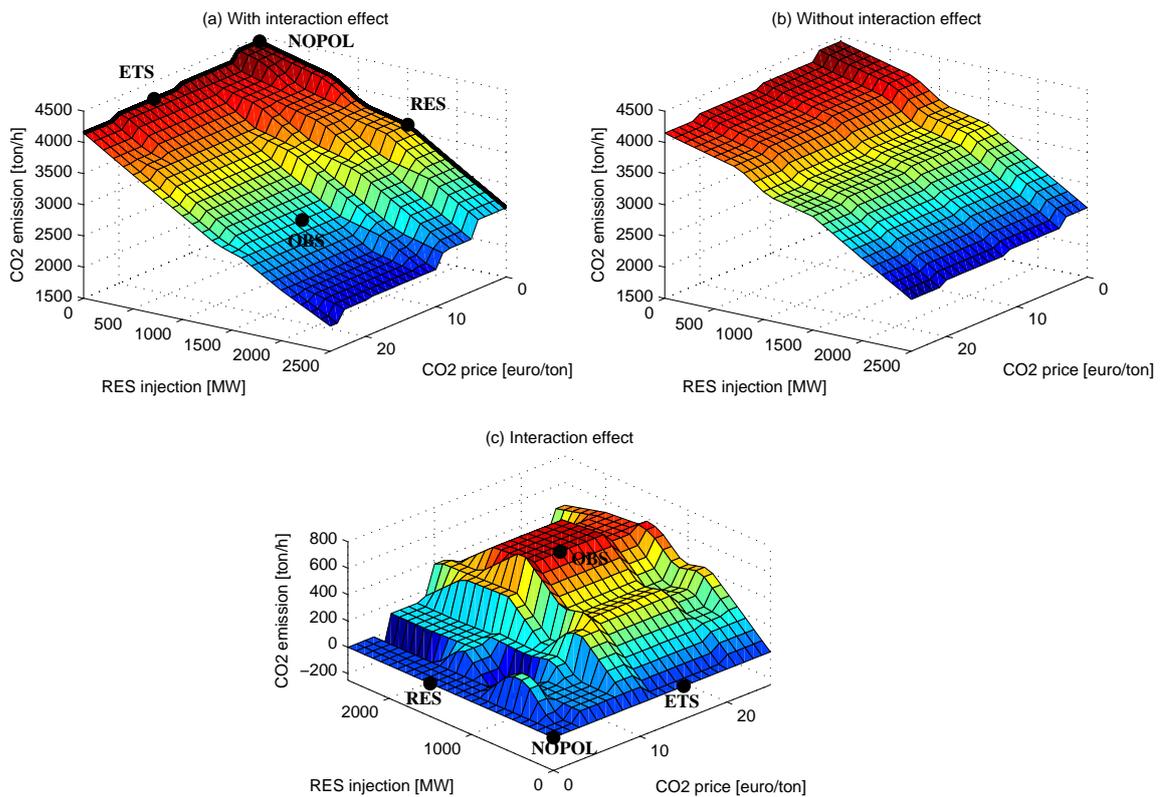


### 5.1.1 Generalization for different CO2 prices and levels of RE injection

This same illustrative system and hour can be used to generate an emissions surface for combinations of RES injections (0 – 2500 MW) and CO2 prices (0 – 25 euro/ton), as presented in panel a of Figure 7 below, where the four scenarios as used above are identified by the black dots. Naturally the highest emissions are observed with no CO2 price and no RE injections (NOPOL). Increasing RE injections (moving along the x-axis) continuously reduces emissions regardless of the CO2 price, albeit at varying rates depending on the generation being displaced. Similarly, increasing the CO2 price also reduces emissions although not continuously reflecting the discrete generating units of this simple example. The other three dots indicate the points where each instrument is used alone and both together in this illustrative case. Panel b of Figure 7 shows a counterfactual without an interaction of ETS and RES. This surface is obtained by simply adding the individual ETS and RES effects (indicated by the upper edges in panel a, where the other instrument takes the value of zero) for the full ranges of each effect. The resulting surface, which would be obtained if there were no interaction, has a more regular shape than the preceding one.

The interaction effect can now be represented by subtracting both surfaces as shown in panel c of Figure 7. Again, the black dots indicate the four scenarios. The interaction effect is zero along the edges when either instrument is used alone, but the general tendency is to take on positive values as either is used in conjunction with the other. However, some chasms of negative values are encountered at high levels of RE injection and low CO<sub>2</sub> prices and in general the interaction effect decreases at high levels of RE penetration.

**Figure 7: Emission surfaces, demand level 6200MW**

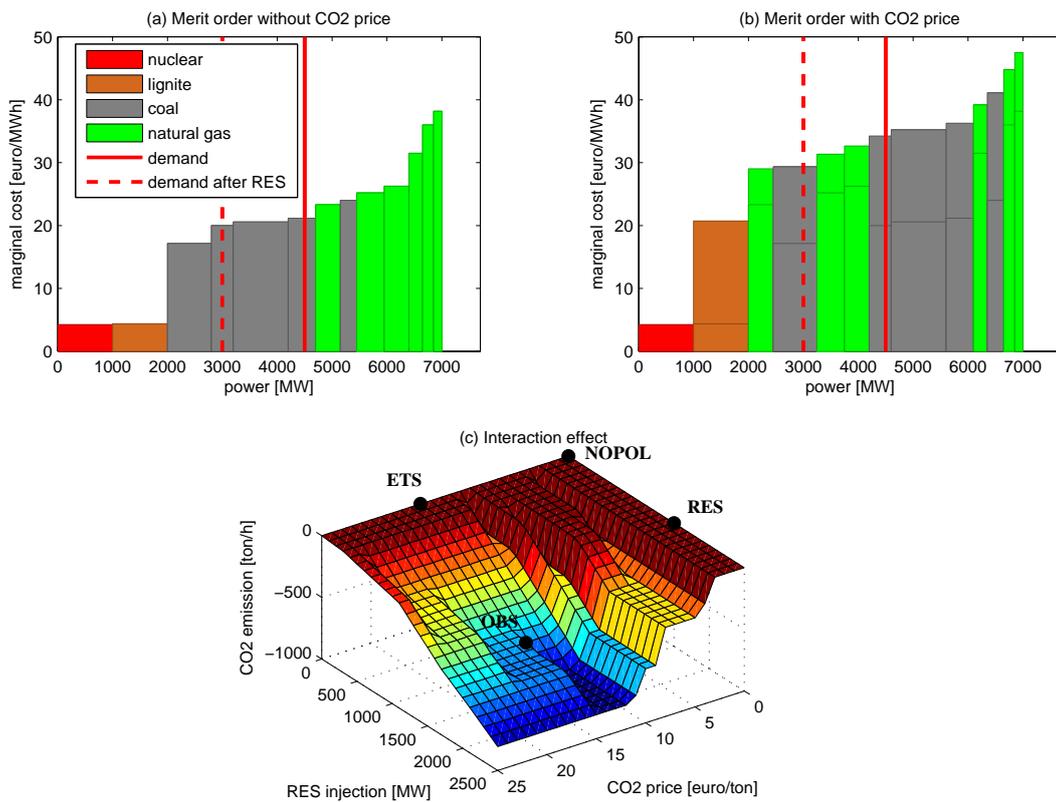


For the considered demand level the interaction is positive over almost the entire range of RE injection and CO<sub>2</sub> prices. However, this result cannot be generalized for other cases. If, for instance, the original demand level is reduced to 4500 MW while maintaining the same dispatch order, the interaction effect reverses, as presented in panel c in Figure 8. In this instance, the interaction effects are always negative, which means that use of both instruments detracts from the effects of each. This can be explained by the merit order shift induced by the CO<sub>2</sub> price (panels a and b in Figure 8).

When demand is this low in the absence of a CO<sub>2</sub> price, all of the gas capacities are in reserve. Consequently, an RE injection displaces only coal. However, when the €15 CO<sub>2</sub> price is present, some of the gas capacity is moved out of reserve and into use and then displaced by the RE injection. More generally, whenever the combination of load and CO<sub>2</sub> price is such as to substitute gas fired

generation for coal into the interval being displaced by the RE injection, the interaction effect will be negative. Similarly, a CO<sub>2</sub> price alone substitutes more gas for coal when there is no RE injection than when the injection is present. As illustrated by this case, using the two instruments together can reduce the abatement that would otherwise be indicated by the use of each instrument alone. As can be seen, the sign of the interaction effect depends on the fuel configuration of existing capacity, load, and the change in dispatch occasioned by the carbon price (or any other change in relative fuel prices).

**Figure 8: Merit order and interaction effect, demand level 4500 MW**



### 5.1.2 Interaction effect as function of RES injection and load

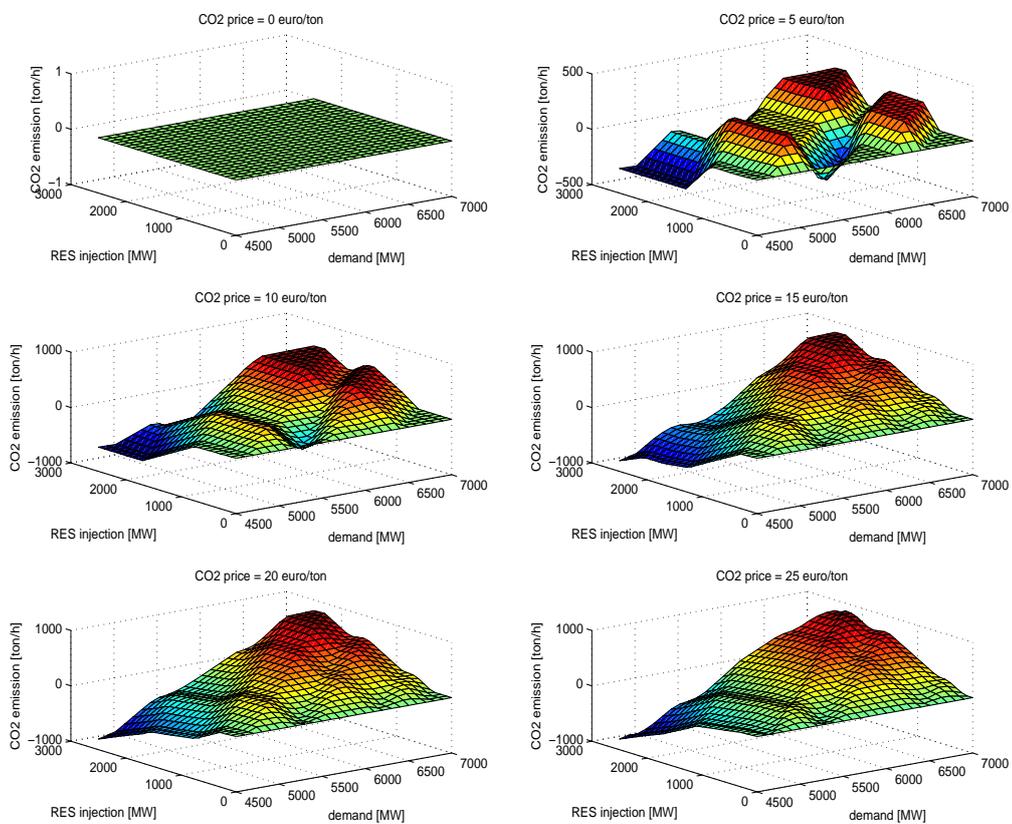
The suggested dependence of the interaction effect on load calls for further analysis of this relation. Just as it was possible to generalize from a specific combination of CO<sub>2</sub> price and RE injection, so the same can be done for the interaction between load and RE injection at different CO<sub>2</sub> price levels.<sup>14</sup> In the interaction surfaces in Figure 9, we vary load level and RES injection

<sup>14</sup> Whereas load level and RE injection vary on hourly level, CO<sub>2</sub> prices are more stable.

continuously for discrete levels of CO<sub>2</sub> prices.<sup>15</sup> Load is assumed to vary between 4500 and 7000 MW, while RE injections are varying between 0 and 2500 MW. Different CO<sub>2</sub> price levels from 0 up to 25 €/ton are considered.

The consistent feature from these diagrams is that negative effects are associated with high RE injection levels and low load. Moreover, the prevalence of these negative effects diminishes with a higher CO<sub>2</sub> price. In all CO<sub>2</sub> price cases, the highest positive values for the interaction term are associated with high RE injections when the demand on the system is high relative to capacity and the positive value tends to be higher with higher CO<sub>2</sub> prices.

**Figure 9: Interaction effect as a function of the RES injection and demand level, for different CO<sub>2</sub> prices.**



## 5.2 Interaction effect in the German system

We now move back from the methodological system to the German one to further explore the observed interaction effect in more detail. However, when the aim is to focus on detailed hourly

<sup>15</sup> Relative fuel prices are also important; however, their impact will be similar to the impact of the CO<sub>2</sub> price. Thus, if gas prices decline relative to coal prices, the result will be similar to that of a CO<sub>2</sub> price in that gas generating capacity will tend to be more utilized and coal less so.

effects, the simulations as presented in Section 3 and 4 are difficult to use, as the model features the use of pumped storage endogenously and considers unit commitment restrictions not included in the simple stacking model. Thus during a specific hour, electricity generation can differ between different scenarios (OBS, RES, ETS, NOPOL), due to a different use of pumped storage and the merit order can also vary due to unit commitment restrictions. Hence, on an hourly basis, the interaction effect cannot be calculated from the hourly emissions of these four scenarios. However, when aggregating on a yearly basis, the difference in pumping more or less nets out due to the similar absolute usage in all four scenarios, making the aggregated results for abatement and interaction meaningful (as discussed in Section 4.1)

To provide reasonable estimates of the interaction effect on an hourly basis, the German data (demand, power plant efficiencies and fuel and CO<sub>2</sub> prices) and simulation results (hourly electricity generation on power plant basis) can however be used to get an indication. The interaction effect is approximated by setting up hourly merit orders (to some extent similar as has been done for the methodological system). This procedure works as follows. First, hourly merit orders are set up with the input data and the generation results from the ETS case (i.e., case with ETS price and without RE injection). The hourly abatement by RE injection is then approximated by calculating the emissions of the generation that would be displaced (according to the merit order) by the RE injection. Second, the same is done (merit order set up and abatement calculation) for the NOPOL case (i.e., no ETS price and no RE injection). The hourly interaction effect is then calculated as the difference between these two abatement levels (the abatement of RE injections when ETS is in place and the abatement of RE injections in absence of ETS prices). This interaction effect is, however, determined purely by the hourly merit orders (effectively considering every hour separately) and therefore not necessarily what would obtain when the power system dynamics involved in operating an electricity network are taken into account. We will denote this interaction without consideration of power system dynamics in the remainder of this text as “pure” or merit order based interaction.

In what follows, the first subsection presents and discusses the course of the pure, hourly interaction effect over the year, while the second subsection contrasts that result with the overall interaction effect (obtained from the four simulated scenarios, when power system dynamics are taken into account).

### **5.2.1 Variation of the “pure” interaction effect over the year**

Given the high variability of load, as well as RE injections, it seems plausible that the interaction effect could change sign and vary considerably over the course of any year. Figure 10 presents the results for 2010 when each hour is treated independently as explained above. Panel a shows the abatement due to RE injections when the ETS is present, panel b the abatement due to RE injections for the same hours when the ETS is not present, and panel c the difference between the two, i.e., the pure interaction effect. Hours are further differentiated between peak (08.00h am till 08.00 pm

on working days) and off-peak.<sup>16</sup> As is evident the interaction effect changes sign frequently and there is no clear difference between peak and off-peak hours. Seasonal patterns can be observed. High positive values for peak hours are found mostly in Oct-Dec and in March. Off-peak hours tend to experience less variation, although in the months of April and May, both peak and off-peak hours show high variability.

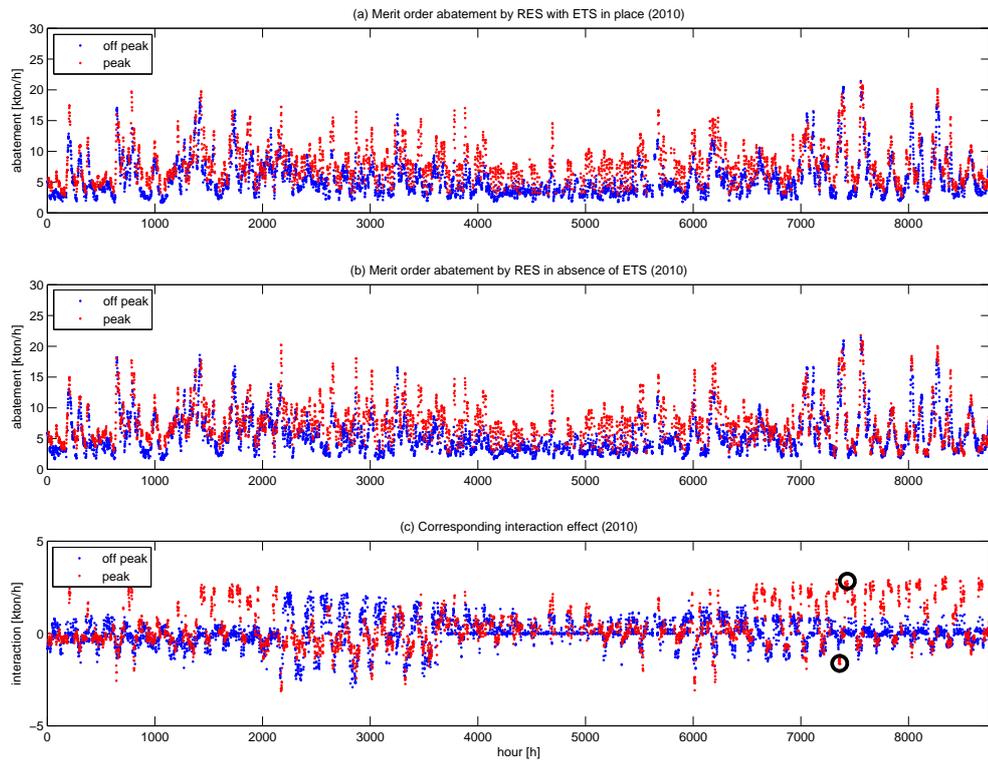
Two peak hours, one with positive interaction effect and the other with a negative effect, are selected for further analysis. These are hours 7360 (Nov 3; 15:00-16:00) and 7431 (Nov 6; 14:00-15:00) and they are indicated by the circles in panel c of Figure 10. Hour 7431 is the one with a positive interaction effect and it is illustrated in Figure 11 and hour 7360 with the negative effect is shown in Figure 12. The positive interaction effect is based on the same principals highlighted by the stylized model: A carbon price moves available, lower emitting gas capacity out of reserve and into use regardless of whether RE injections are present or not (albeit by different amounts). And, since higher emitting coal generation is moved closer to the margin, RE injections reduce more emissions when the carbon price is present than when it is not.

The negative interaction effect occurs just a few days earlier and at almost the same time of the day. As can be seen by comparing Figures 10 and 11, the main differences are that peak load for this hour was lower, 52 GW (instead of 60), and the RE injection was larger, 16 GW (instead of 10 GW). The merit order under those conditions is such that mainly coal plants are utilized when there is no carbon price (NOPOL). In the ETS case, gas units are shifted out of reserve into the dispatch. Under these conditions, the RE injection replaces only coal plants in the ETS-free setting while the same injection replaces a mix of coal and gas plants with an ETS price. Thus, when a carbon price is present, the RE injection abates less than it would have without the carbon price, thereby creating the negative interaction effect.

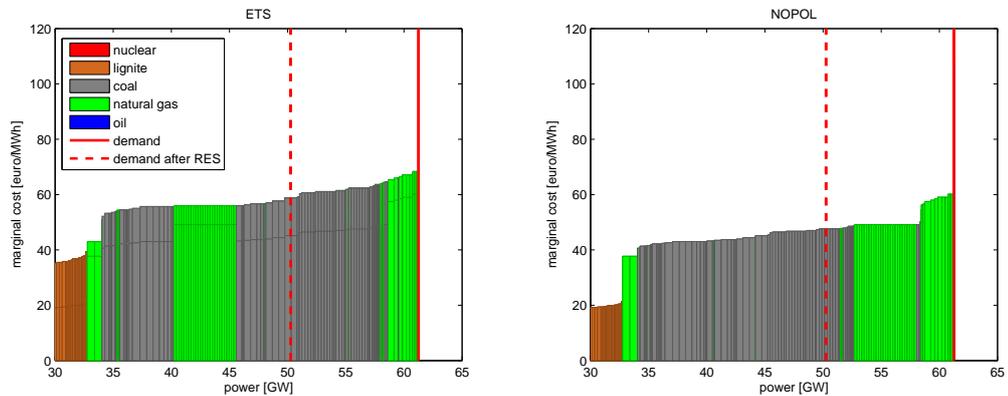
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<sup>16</sup> The reason to make this distinction is mainly driven by the fact that in calibrating the model, different cost-markups are applied in peak and off-peak periods, for different fuels/technologies. These mark-ups are also taken into account in this merit order based analysis.

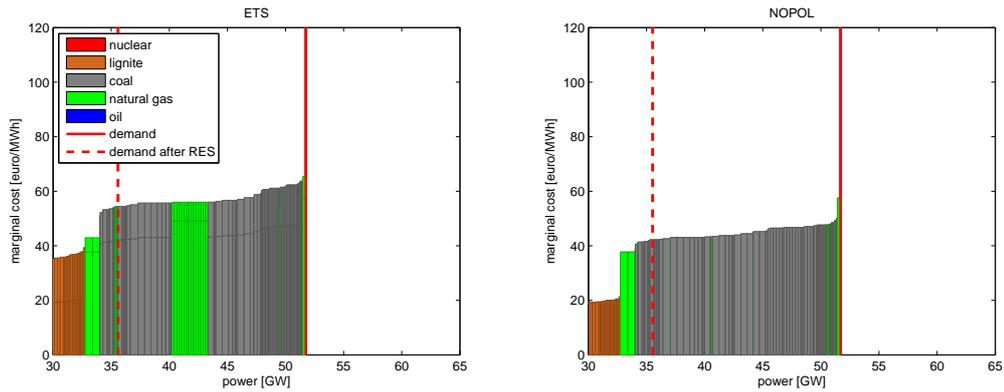
**Figure 10: Hourly abatement by RES, in case with ETS in place (a) and in absence of ETS (b), and corresponding interaction effect (c).**



**Figure 11: Merit orders during hour of positive interaction effect (hour 7431, year 2010)**



**Figure 12: Merit orders during hour of negative interaction effect (hour 7360, year 2010)**

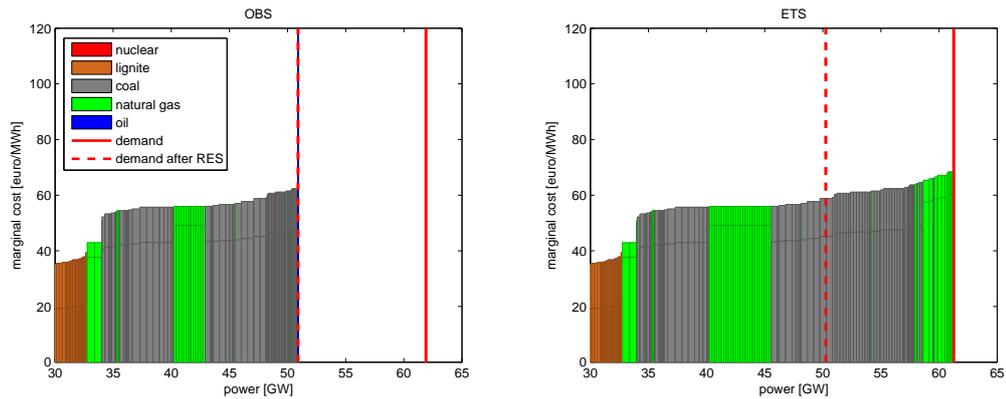


### 5.2.2 The interaction effect with system constraints and comparison for Germany 2006 - 2010

The discussion under Section 5.2.1 has treated each hour as if that hour was independent of dispatch in the preceding hours or expected dispatch in the succeeding hours (as hourly merit orders were used to obtain the interaction effect). In any real electricity generating system with start-up and minimum down time constraints, the pure interaction effect (as illustrated in the previous section) is clearly not the end of the story. The question arises then of the extent to which these system dynamics change abatement from RE injections and carbon pricing and how they affect the interaction effect that we have observed.

When aggregated over all hours of the year, the pure interaction can be compared with the interaction effect obtained from the four scenario runs of the German simulation model (see Section 4.1). The difference between this aggregated pure interaction and that obtained from the model runs provides an estimate of the impact of system dynamics on the interaction. That there is a difference becomes obvious when comparing, for instance, the merit order of the OBS and the ETS setting of the previously considered hour 7431 of 2010 as presented in Figure 13 (the RHS panel of this figure is identical to the LHS panel of Figure 11). Note that for this specific hour, these different scenarios can be compared as demand is more or less equal.

**Figure 13: Merit orders for the OBS and ETS case (hour 7431, year 2010)**



The dotted line indicates the residual demand level accounting for RE injection. In the OBS case this is the relevant demand for conventional plants and the merit order reflects the considered least-cost dispatch accounting for unit commitment and pumped storage. The ETS case presented here has been used to determine the “pure” interaction effect without consideration of system dynamics as explained in section 5.2.1. Injecting the amount of RE observed in this hour would indicate the merit order shown to the left of the dotted line, which is clearly different from that obtained for this hour when system dynamics are included. The system dynamics keep more coal plants on line, which suggests that the abatement from the RE injection is being overestimated (in the calculation of the pure interaction effect), thereby diminishing if not reversing the positive pure interaction effect for this hour. The relevant aggregate indicator of these complex interactions is the annual value to which we now turn.

Table 2 sums the relevant measures for all hours for the considered years, 2006-2010, and provides estimates for the pure merit order effects and those caused by system dynamics.<sup>17</sup> The pure merit order based abatement by RES and interaction effect is determined by setting up hourly merit orders, as applied in the previous subsection (derived from the ETS and NOPOL cases). The overall interaction effect is derived from the four simulation scenarios (with full system effects, as discussed in Section 4.1). The difference is attributable to system dynamics.

<sup>17</sup> Note that for those estimates conventional plants exclude CHP units as those are considered heat driven and thus exogenously to the dispatch decision and treated like RE injection reducing the residual demand level.

**Table 2: Pure and system dynamic interaction effect estimates for Germany (Mtons CO2)**

		2006	2007	2008	2009	2010
<b>Abatement by RES</b>						
w ETS	With system dynamics	33,23	37,31	52,64	52,43	54,90
	Without system dynamics	35,25	40,97	53,97	53,59	57,07
w/o ETS	With system dynamics	31,71	37,14	47,60	49,70	51,20
	Without system dynamics	34,91	40,79	51,56	52,50	55,73
<b>Interaction effect</b>						
Interaction term with system dynamics		1,52	0,17	5,04	2,73	3,71
Interaction term without system dynamics (= pure interaction effect)		0,34	0,19	2,42	1,09	1,34
Effect of modeled system dynamics		1,18	-0,02	2,63	1,63	2,36

The results for Germany indicate that the aggregate, annual interaction effect is positive for all years, although negligible in 2007 when the carbon price is low. The estimates for the share of the pure interaction effect and the influence of system dynamics vary over the years but indicate that there is indeed a significant impact of both.

The aim here is merely to demonstrate the existence of these interaction effects, together with the fact that they can fluctuate heavily over time, rather than to provide detailed quantitative results. After all, the German model has not been designed to address this issue in the first place<sup>18</sup> and thus the derived numbers are only estimates. The interaction effect attributable to system dynamics is calculated as the difference between the overall interaction effect (from the simulation) and the aggregated pure interaction effect (over the full year). Hence, no hourly values are available for this system dynamics interaction, making a detailed exploration and explanation difficult. But what already is clear is that this interaction is highly dependent on specific power system characteristics and constraints. A comparison between two model runs, one with and one without system dynamics, would be needed to make a more thorough reliable assessment.

## 6 Conclusion

This paper started out as an exploration of the extent to which RE incentives have reduced the demand for allowances from the German electricity sector in actual practice. The answer to that question turned out to be more complicated than expected because abatement resulting from any given injection of RE generation depends on the carbon content and the merit order of the displaced generation. In general, a carbon price (but also a rise or fall in relative fuel prices) changes the merit order and thereby causes abatement from RE injections to be greater or smaller than it would otherwise be depending on the change in merit order within the interval of generation displaced by the

<sup>18</sup> Especially the cost markup calibration merits careful caution in this regard.

RE injection. We have termed this extra abatement an interaction effect, but it must be kept distinct conceptually from price interaction that has received attention in the literature.

In the case of the German electricity system for the years 2006 through 2010, RE policy reduced CO<sub>2</sub> emissions from the electricity sector by between 33 and 57 Mtons, or 10% to 16% of what we estimate emissions would have been without any policy, depending on the year and whether the CO<sub>2</sub> price was present or not. The German electricity sector accounts for about 15% of the emissions included within the EU ETS so that even a 16% reduction in the demand for allowances from this component translates into a system-wide reduction in demand of only 2.4%. Still, when the abatement required by the cap is measured in the single digits as a percentage of what emissions would have been without a carbon price, this is not an insignificant reduction in demand. For instance, and as a matter of simple geometry, if the required abatement system-wide is 5% and the marginal abatement cost curve is linear, EUA prices would be nearly 50% higher than what has been observed. However, absent reliable estimates of the system-wide marginal abatement cost curve or of what emissions would have been in the absence of climate policy, such estimates of EUA price effect are speculative.

When measured on an annual basis, the interaction effect is consistently positive for the German electricity system and on the order of 0.5% to 1.5% of emissions for all years, except in 2007 when the CO<sub>2</sub> price was effectively zero. Given our estimates of No-Policy emissions, this additional effect increases the CO<sub>2</sub> abatement due to RE incentives by 4% to 10% and that of the EUA price by 50% to 130%, always depending on the year. However, when the year is broken down into its component hours, the interaction effect varies widely and changes frequently for both peak and off-peak hours. Further analysis of the determinants of this interaction effect show that its sign and value depend on the load in each hour and the effect of the carbon price on the merit order within the interval of generation that is displaced by the RE injection. The summed annual interaction effect turns out to be positive because the CO<sub>2</sub> price more often replaces gas with coal than the reverse in the generation interval that is being displaced by the RE injection.

This summed positive annual effect will generally occur when the CO<sub>2</sub> price puts coal on the margin in place of gas and the RE injection is not so large that it is displacing gas plants that have been moved down the merit order by the CO<sub>2</sub> price and thereby replacing coal. As we have shown, when the combination of load and RE injection is such that the displaced marginal interval includes more segments in which the CO<sub>2</sub> price has caused gas to replace coal, the interaction effect is negative. Eventually, as the RE injections increase in volume and displace increasing amounts of fossil generation, the interaction term will become increasingly negative. And, if the RE injections were ever to become so great as to replace all fossil-fired generation, the carbon price will have no effect on the ordering of the remaining in-use generation (nuclear, hydro, etc.) and the summed interaction effect will be the negative equivalent of the ETS impact in absence of RE injections. Thus, a positive interaction effect will always disappear if the RE injection is large enough.

All research operates under limitations usually reflecting model structure and various maintained assumptions. One limitation of our research is that the CO<sub>2</sub> price is not endogenous to the model so that we cannot model an appropriate CO<sub>2</sub> price with the ETS case when there are no RE injections. In effect, we treat the observed CO<sub>2</sub> price reflecting the demand-suppressing effect of actual ETS-wide RE injections as a fixed price – equivalent to a tax – that does not vary with factors that would otherwise increase or lower the demand for allowances. However, the model can estimate the effect of a higher CO<sub>2</sub> price on fuel switching in Germany, which reduces the displaced abatement elsewhere in the EU ETS. Still, the net effect of the RE injections is clearly to reduce demand for allowances and to suppress the EUA price by some amount.

Another limitation of our analysis concerns system interactions that are unique to electricity systems. Most of our explanation of the interaction effect is conducted on the assumption that each hour stands alone and that system constraints and characteristics do not cause the generation in any given hour to depend on generation in preceding or succeeding hours. The simulation model, however, respects unit commitment and the effect of pumped storage in smoothing peaks and valleys. When these constraints are imposed, the aggregate annual interaction effect is obtained and turns out positive. We find that about half of this aggregate is due to system dynamics rather than pure merit order based effects.

Finally, for all the interest that this abatement interaction effect holds, it is relatively small at least at the CO<sub>2</sub> prices that have been observed. Our analysis suggests that it would be larger with higher CO<sub>2</sub> prices (or the lower gas prices relative to coal prices), but even so, the bigger factor in explaining the reduced demand for allowances is the direct reduction of CO<sub>2</sub> emissions by RE injections. These injections are more effective in reducing CO<sub>2</sub> emissions than the EUA price, at least at the levels observed so far in the EU ETS. Whereas a carbon price tends to substitute lower emitting gas generation for coal generation, RE injections displace whatever is on the relevant margin with a zero-CO<sub>2</sub>-emitting source. The displacement occurs without regard to the carbon content of the displaced generation, but in existing electricity systems this is nearly always CO<sub>2</sub>-emitting fossil generation. Hence, the large abatement effect and consequent reduction in the demand for allowances within the EU ETS.

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## Appendix

**Table 3: Result overview, base cases**

	Observed	BAU	No ETS	No RES	No ETS/RES
<b>2006</b>					
EUA price: 17.2€/t, total generation: 636.5TWh, RES injection: 50.3TWh					
Price [€/MWh]	50.79	51.01	38.67	63.88	53.17
Coal output [TWh]	137.9	147.3	153.8	169.2	173.5
Gas output [TWh]	73.4	76.1	69.8	98.9	94.6
Gen costs [bn €]		18.8	13.5	21.7	15.9
Con costs [bn €]	31.8	32.0	24.2	40.1	33.3
<b>2007</b>					
EUA price: 0.6€/t, total generation: 640.0TWh, RES injection: 64.0TWh					
Price [€/MWh]	37.99	32.28	31.54	52.81	52.40
Coal output [TWh]	142	155.3	155.5	173.6	173.6
Gas output [TWh]	75.9	75.1	74.9	114.3	114.3
Gen costs [bn €]		12.3	12.1	14.8	15.0
Con costs [bn €]	23.7	20.1	19.7	33.0	32.7
<b>2008</b>					
EUA price: 17.2€/t, total generation: 638.4TWh, RES injection: 71.3TWh					
Price [€/MWh]	65.86	68.15	54.98	87.38	75.82
Coal output [TWh]	124.6	133.3	150.2	173.9	180.8
Gas output [TWh]	86.7	86.7	70.7	112.5	105.3
Gen costs [bn €]		23.1	18.1	28.9	23.0
Con costs [bn €]	40.6	42.0	33.9	53.9	46.8
<b>2009</b>					
EUA price: 13.2€/t, total generation: 600.0TWh, RES injection: 73.6TWh					
Price [€/MWh]	39.57	40.31	30.12	58.06	48.18
Coal output [TWh]	109	123.1	134.2	161.3	167.9
Gas output [TWh]	77	80.9	69.3	103.3	96.2
Gen costs [bn €]		15.3	11.6	19.1	14.6
Con costs [bn €]	23.1	23.6	17.6	34.0	28.2
<b>2010</b>					
EUA price: 14.9€/t, total generation: 627.0TWh, RES injection: 79.1TWh					
Price [€/MWh]	44.49	46.36	35.32	66.28	56.74
Coal output [TWh]	109	111.7	122.8	152.1	160.2
Gas output [TWh]	77	78.2	67.0	100.0	91.6
Gen costs [bn €]		17.5	13.2	22.2	17.1
Con costs [bn €]	27.5	28.6	21.8	41.0	35.1

**Table 4: Interaction effect, base cases [Mton]**

	Measured from BAU			Measured from counter factual		
	ETS effect	RES effect	combined	ETS effect	RES effect	combined
<b>2006</b>						
Coal	6.2	20.6	24.7	4.1	18.5	24.7
Gas	-2.4	10.6	9.0	-1.6	11.4	9.0
Total	3.8	34.5	37.0	2.5	33.2	37.0
<b>2007</b>						
Coal	0.2	17.3	17.3	0.0	17.1	17.3
Gas	-0.1	18.1	18.1	0.0	18.2	18.1
Total	0.1	39.3	39.3	0.0	39.2	39.3
<b>2008</b>						
Coal	16.1	38.2	45.0	6.8	28.8	45.0
Gas	-7.2	12.4	9.1	-3.3	16.3	9.1
Total	8.8	54.0	57.9	3.9	49.0	57.9
<b>2009</b>						
Coal	10.6	35.3	41.6	6.3	31.0	41.6
Gas	-5.1	10.5	7.3	-3.2	12.4	7.3
Total	6.2	53.9	57.5	3.6	51.3	57.5
<b>2010</b>						
Coal	15.6	36.2	45.8	9.6	30.1	45.8
Gas	-7.1	16.4	11.9	-4.5	19.0	11.9
Total	8.6	56.5	61.6	5.1	53.0	61.6

**Table 5: Result overview, differentiated RES cases**

	No Wind	No Solar	No Bio	No Bio&Solar	No Wind&Solar	No Wind&Bio	No RES
<b>2006</b>							
Merit order effect [€MWh]	6.47	0.32	3.52	4.74	7.13	10.95	12.87
FIT [€MWh]	4.36	1.88	2.44	4.32	6.24	6.81	8.68
Emissions reduction [%]	7.3	0.5	4.2	4.6	7.7	10.8	11.2
<b>2007</b>							
Merit order effect [€MWh]	10.41	1.02	6.58	7.45	12.59	17.94	20.53
FIT [€MWh]	5.67	2.95	3.61	6.56	8.62	9.27	12.22
Emissions reduction [%]	8.1	0.6	4.4	5.0	8.7	11.8	12.3
<b>2008</b>							
Merit order effect [€MWh]	5.52	0.66	3.37	6.89	8.43	16.24	19.23
FIT [€MWh]	5.74	3.31	4.69	8.00	9.05	10.43	13.74
Emissions reduction [%]	10.7	1.2	7.2	8.4	11.8	17.1	18.2
<b>2009</b>							
Merit order effect [€MWh]	6.02	2.14	5.19	8.22	9.14	15.54	17.75
FIT [€MWh]	5.80	5.39	6.57	11.96	11.20	12.37	17.77
Emissions reduction [%]	10.5	1.6	8.3	9.7	11.9	18.0	19.1
<b>2010</b>							
Merit order effect [€MWh]	3.40	3.05	5.51	9.76	8.20	13.76	19.93
FIT [€MWh]	7.52	6.81	7.16	13.97	14.33	14.68	21.49
Emissions reduction [%]	9.2	2.5	8.5	11.0	11.8	17.3	19.7