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Decoupling the EU ETS from subsidized renewables and other demand side effects

Lessons from the impact of the EU ETS on CO_2 emissions in the German electricity sector

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Abstract

This paper analyzes the impact of the EU ETS on CO_2 reduction in the German electricity sector. We find an ETS-induced emission abatement which is not exceeding 6 % of total emissions with a maximum already in 2010. Thereafter the ETS has not induced additional reductions. This outcome is sub-optimal. It corresponds to the recent debate about sub-optimal performance of the EU ETS caused by excessive allowances. Following up on this we develop a unilateral flexible cap to eliminate demand side effects which lead to excessive allowances. The unilateral flexible cap is based on emission intensities. Using the works of Newell and Pizer (2008); Sue Wing *et al.* (2009) we prove in a first step that an intensity-based emission cap is advantageous in the German electricity sector when compared to an absolute cap. An ex-post analysis shows that the amount of excessive allowances resulting from the economic crisis during the second trading period could have been significantly lowered with a unilateral flexible cap. This approach also decouples the EU ETS from a simultaneous promotion of renewable energy.

Keywords Decoupling Overlapping Regulations, Promotion of Renewable Energy, Emissions Trading, Intensity Standard
JEL Q41, Q42, Q48, Q54

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1 Introduction

Since 2009 the price for emission allowances of the EU emissions trading system (ETS) has faced a massive drop. De Perthuis and Trotignon (2014) identify three main reasons for it. First, they point at an oversupply of allowances caused by the possibility to credit emission reductions outside the EU towards the EU ETS. Second, they find lower demand on allowances induced by overlapping regulations (e.g. promotion of renewable energy). Third, they identify the economic crisis of 2008 which affected demand, too. The persistent price drop has led to doubts whether the EU ETS is able to set sufficient incentives for investments in emission abatement (De Perthuis and Trotignon, 2014).

There is a number of studies assessing the success of the EU ETS with respect to CO_2 reduction (see Laing *et al.*, 2013, for an overview). Most studies compare reported emissions with a counterfactual scenario without ETS (Ellerman and Buchner, 2008; Ellerman *et al.*, 2010; Anderson and Di Maria, 2011; Egenhofer *et al.*, 2011). These studies project (limited) data before introduction of the ETS to the future to construct the counterfactual scenario. In contrast, Widerberg and Wråke (2011) carry out an empirical analysis based on data for the Swedish electricity sector to identify the drivers of changes in emission intensity. Other authors focus on certain ETS-induced effects as fuel switching (Delarue *et al.*, 2008) or innovation (Rogge *et al.*, 2011) to explain emission changes.

We use an approach similar to the work of Widerberg and Wråke (2011) based on annual data of the German electricity sector. In contrast to their results for Sweden we find a significant impact of the allowance price on emission intensity in the German electricity sector. However, the time trend is the strongest driver of emission reduction. We find an ETS-induced emission reduction which is not exceeding 6 % of total emissions with a maximum in 2010. Thereafter the ETS has not induced additional reductions in the German electricity sector at all. The observed emission reduction in the German electricity sector has not complied with expectations. These findings are the starting point to consider an adjustment of the EU ETS with respect to the three main causes for price erosion identified by De Perthuis and Trotignon (2014).

Price erosion by supply-side effects is an issue of simple direct regulation. Indeed the EU has limited the possibility to credit emission reductions outside the EU towards the EU ETS starting from 2013 (European Commission, 2013a). In this chapter we analyze the possibility to eliminate price erosion from demand-side effects (e.g. overlapping regulations, business cycles) by stating emission targets in relation to output or GDP instead of an absolute cap. In the literature such targets are mainly known as rate-based, intensity-based or indexed.

Fisher (2003) and Holland (2012) point out that a purely output-related emission objective means a subsidy for output. Companies with lower emissions than the intensity standard "print" allowances with each output unit they produce. According to Sue Wing *et al.* (2009), this critique does not apply on an aggregated level. Furthermore, it does not apply to the model described below because we will suggest an output-related emission objective only in addition to the absolute cap for its ex-post adjustment.

Quirion (2005); Newell and Pizer (2008) develop models to evaluate intensity-based emission objectives. Both papers are based on the seminal work of Weitzman (1974). Quirion (2005) finds little justification for an indexed regulation since a tax-based regulation is very likely to be superior. Newell and Pizer (2008) point out that a tax is often unfeasible. Thus, the decision usually is up to absolute quantities or intensity-based quantities. This corresponds to the situation of the EU ETS. Newell and Pizer (2008) derive a mechanism to find out which of these two options is more effective. Sue Wing *et al.* (2009) set up a similar approach based on Ellerman and Sue Wing (2003) which, for simplicity, neglects marginal damage and focuses on cost minimization only.

Applying the methods suggested by Newell and Pizer (2008) and Sue Wing *et al.* (2009) to data of the German electricity market provides a clear result. An intensity-based emission cap is preferred to an absolute cap in recent years. However, an intensity-based emission cap cannot guarantee to reach an absolute objective (Rathmann, 2007). Thus, we suggest a combination of absolute and intensity-based cap. The intensity-based cap is used to adjust the absolute cap only for lower electricity generation than expected. An adjustment for unexpected high electricity generation is not necessary because the EU ETS already provides mechanisms with regard to a limitation of the certificate price (European Parliament and Council of the EU, 2009). The result of our approach is a unilateral flexible cap which eliminates demand side effects by an automatic reduction of certificates.

The EU, in contrast to our approach, in 2015 introduced the so-called market stability reserve which intended a delayed auctioning of excessive allowances (European Parliament and Council, 2015). Nevertheless, prices did not significantly recover. Only after the agreement between the European Parliament and the Estonian presidency of the Council of the EU on November 9, 2017 allowance prices have significantly recovered. In contrast to the 2015 decision of the European Commission more excessive certificates are absorbed by the market stability reserve and the reduction objectives for post 2020 have been exacerbated. The most important change was probably, that excessive allowances above a certain threshold value will be deleted from the reserve.

The advantage of our approach is that it follows a clear and predictive mechanism while the EU regulation is vulnerable to lobbying. This particularly applies for the threshold value kept in the market stability reserve and the speed excessive allowances are collected. Both were already changed between 2015 and 2018 (European Parliament and Council, 2015; European Parliament and Council of the EU, 2018). The threshold value also weakens the effectiveness of the procedure because demand side effects still have a significant impact. Moreover, the deletion of allowances at the end of 2023 is a single event so far. The decision was made under great difficulties in a lengthy process which took almost four years. Described deficiencies are avoided with the suggested unilateral flexible cap.

As basis for the following analysis we briefly describe the functioning of the EU ETS with a focus on the German electricity sector in the next section. In Section 3 we develop an easy empirical model to evaluate the emission reduction induced by the EU ETS. The effectiveness of an intensity-based emission cap is evaluated in Section 4. Moreover, we introduce the unilateral flexible cap and discuss its impact on emission reduction.

2 The EU ETS in the German electricity sector

For the first two trading periods of the EU ETS, National Allocation Plans (NAPs) were developed in each participating country. These plans specified, in the context of existing commitments, the national emissions budget (macro plan) and the allocation of allowances (micro plan). The NAPs had to be approved by the European Commission. In Germany the allocation to operators of power plants was based on historical data of a base period which contained the years 2000 till 2002 (Federal Ministry for the Environment, 2004, p. 8).

The German NAP for the first trading period (2005 – 2007) intended to cap emissions from 501 Mt per year in the base period to 499 Mt per year. The target was set as an intermediate step to reach the goals for 2012, stipulated in the Kyoto Protocol. The cap of annually 499 Mt also included certificates for privileged operators (early action, reserve for new installations etc.). This reduced the cap to 489 Mt/year for non-privileged operators which meant an intended reduction of 2.4 % when compared to the base period (Federal Ministry for the Environment, 2004). In retrospect, it turned out, that the assumed amount of emissions in the base period for the sectors which were underlying the ETS was wrong. Instead of assumed 501 Mt/year emissions only amounted to 482.4 Mt/year in this period (Federal Ministry for the Environment, 2006, p. 49, footnote 14). The number of annual certificates for non-privileged operators thus exceeded annual emissions of the base period by 1.4 % instead of the intended reduction of 2.4 %.

In the second trading period (2008 – 2012) the number of facilities underlying the ETS increased. The German government assumed an increase of 11 Mt/year with respect to the base period yielding a total amount of 493.4 Mt/year for 2000 – 2002. The respective NAP intended a reduction to 482 Mt/year which meant a decrease of CO_2 by 2.3 % (Federal Ministry for the Environment, 2006). This allocation plan was rejected by the European Commission. Amongst other things the European Commission criticized that likely emission reductions which are not induced by the EU ETS were not considered. The Commission claimed at least to consider an annual decrease in emission intensity (ratio of emissions and GDP) of 0.5 % (European Commission, 2006).[1]

The revised NAP eventually intended a reduction to 456.1 Mt per year. This cap also considered 3 Mt/year for additional facilities and included certificates for privileged operators. Overall the cap meant an intended emission reduction of 8.1 % when compared to the base period. However, the intended emission reduction for the industrial sector was only 1.25 % leading to a correspondingly higher reduction in the energy sector. According to the NAP, the number of allowances for the energy sector was limited to a maximum of 311.1 Mt per year [2] while emissions in the base period were 496.4 Mt - 125 / 0.9875 = 369.8 Mt per year (Federal Ministry for the Environment, 2007). This meant an intended reduction of 13.8 % in the electricity sector when compared to the base period.

Another innovation in the second trading period was the introduction of the Joint Implementation (JI) and the Clean Development Mechanism (CDM). These mechanisms allow to count credits, so-called Certified Emission Reductions (CERs) and Emission Reduction Units (ERUs), for emission reduction carried out in developing and emerging countries towards emissions in the EU ETS. CERs and ERUs which were issued during the second trading period could be exchanged to allowances of the EU ETS until March 31, 2015 (European Commission, 2013b). Until April 30, 2015 1.445 billion international credits were used in the EU ETS or exchanged to allowances valid in the EU ETS. It is expected that the EU-wide number of CERs and ERUs continues to increase until the end of the third trading period up to 1.6 billion certificates (European Commission, 2015, annex 1, p. 17). In addition a substantial surplus of allowances occurred caused by the last financial and economic crisis, which

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[1] In Section 3 we find for the German electricity sector a non-ETS-induced decrease of 0.5 % in output-related emission intensity (ratio of emissions and electricity output).

[2] The total amount of 456.1 million certificates is reduced by 125 million certificates which are allocated to the industrial sector while 20 million allowances were reserved for new facilities.

amounts to 650 million certificates all over Europe (Neuhoff and Schopp, 2013).

Already by these two effects, the surplus of emission allowances can be expected to exceed the total anticipated emission reduction for the third trading period which amounts to about two billion tons (European Commission, 2012a). Compared to the second trading period, up to 2020 no additional savings within the EU are required. The surplus of certificates indeed amounted to around 2.1 billion in 2013 (European Commission, 2017). Although the European Parliament decided to shift auctions of 900 million certificates from the period 2014 – 2016 to 2019 – 2020 (European Commission, 2014) the surplus decreased to 1.78 billion certificates in 2015 and 1.69 billion in 2016 (European Commission, 2017) which is eventually a decrease of only 400 million certificates.

From the start of the third trading period (2013 – 2020) several changes were introduced to the EU ETS. The number of CERs and ERUs valid in the EU ETS has been limited while the requirements for admission of projects has been tightened (European Commission, 2013b). Instead of NAPs an EU-wide cap has been introduced. This cap is based on the average of certificates $\bar{E}_{2008-2012}$ which were issued in the second trading period. This average of issued certificates is reduced by a linear factor of 1.74 % starting from 2010 (European Commission, 2010). The EU-wide cap for 2013 is thus equal to $E_{2013} = (1-3\cdot 0.0174)\bar{E}_{2008-2012}$ amounting to 2,084,301,856 allowances which are reduced every year by 38,264,246 allowances (European Commission, 2012a).

3 CO_2 reduction in the German electricity sector

In a first step of our analysis we recall possible mitigation strategies on the side of electricity supply to find a suitable indicator for emission reduction induced by the ETS. On the one hand generators can substitute emission-intensive energy sources by less emission-intensive sources (substitution strategy). Switching electricity generation for instance from coal to gas reduces emissions. On the other hand emission reduction without fuel switching always requires lower fuel input per generated electricity output (efficiency strategy) because CO_2 reduction by carbon capturing and storage (CCS) is not competitive in electricity generation (Schröder *et al.*, 2013). Progress in research and development or the use of waste heat can for example bring efficiency gains.

In addition to these two general strategies for emission reduction CO_2 is sensitive to demand side effects. If the allowance price leads to higher electricity prices it has an impact on demand. Nevertheless, an optimal abatement means preferably low costs. Other effects as business cycles and weather also influence demand and thus emissions but they are independent of the ETS. Therefore, it is expedient to use an indicator which considers emission reduction of the supply side while it neglects the demand side. Using the emission factor which corresponds to emissions per electricity output (output-related emission intensity) instead of absolute emissions satisfies this condition.

In order to calculate the emission intensity for the German electricity sector we need to find out emissions and electricity generation which is underlying the EU ETS. We can reasonably assume that all German fossil power plants underly the EU ETS (Schäfer, 2018). Total emissions of the electricity sector are calculated based on data provided by Working Group on Energy Balances (2018b), Federal Environment Agency (2018) and Statistics of the Coal Sector (2018) (see Appendix A, Table 6 for results).

For the calculation of electricity generation in the sphere of the EU ETS two peculiarities must be considered for Germany. First, electricity generation from nuclear power plants did not increase after 1989 and Germany decided the nuclear phase-out until 2022. Nuclear power plants are thus no possibility for fuel switching. Second, incentives of the EU ETS are not sufficient to substitute fossil by renewable energy sources (RES) as long as additional subsidies are necessary. In contrast non-promoted RES can be affected by an ETS. Electricity generation in the sphere of the EU ETS thus arises subtracting electricity which is generated by nuclear power plants (Working Group on Energy Balances, 2018b) and subsidized RES (Information Platform of the German Transmission System Operators, 2018; Wagner, 2000) from total electricity output (Working Group on Energy Balances, 2018b).

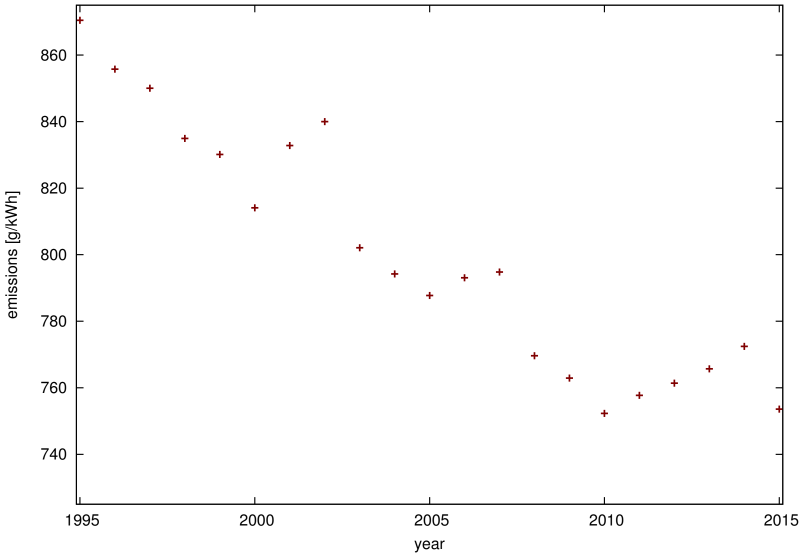

Figure 1: Development of emission intensity in electricity generation from 1995 until 2015. Own calculations based on Working Group on Energy Balances (2018b), Federal Environment Agency (2018) and Statistics of the Coal Sector (2018).

The development of emission intensities from 1995 until 2015 is given in Fig. 1. There is a significant decrease of emission intensities during this period of time. Emission intensities seem to underly a rather strong time trend. The decreasing trend is interrupted three times (2001 – 2002, 2006 – 2007 and 2011 – 2014). In this context the following events linked to the EU ETS may deliver an explanatory approach although there is no proof.

On March 8th 2000 the Commission of the European Communities published the Green Paper (Commission of the European Communities, 2000) presenting possibilities for the introduction of an ETS. According to Convery (2009), "*the tone and tenor of the paper assumed that the decision to proceed and establish a Community wide emissions trading scheme had already been taken*". The paper also mentioned the possibility to allocate certificates to participants based on historical emissions. Thus, it was apparent that the ETS would be introduced and that higher historical emissions could be an advantage with respect to allocation. This meant an incentive for generators to raise emissions in the hope of a more generous allocation of certificates during the first trading period. Worth mentioning is that before introduction of the EU ETS there were no strict reporting obligations about emissions.

Indeed, the German government decided on May 28, 2003 that allowances should be allocated to generators based on their historical emissions in the years 2000 – 2002 (Federal Ministry for the Environment, 2004, p. 8). This decision canceled the incentive to continue raising emissions. In sum, this situation might be one reason why emission intensities in 2001 and 2002 broke the time trend.

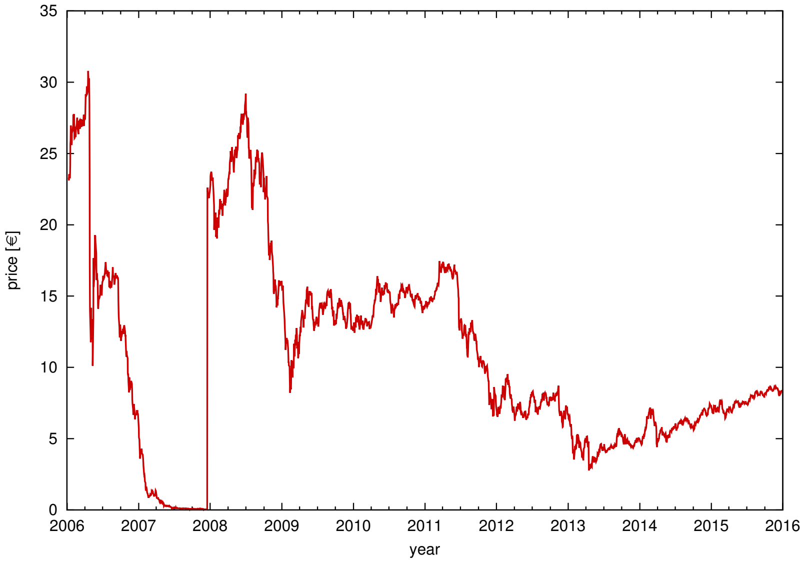

Figure 2: Development of the allowance price of the EU ETS between 2006 and 2016. Own illustration based on Intercontinental Exchange (2018).

Increasing emission intensities in the periods 2006 – 2007 and 2011 – 2014 more or less correspond to phases with low allowance prices (see Fig. 2). On the one hand incentives for emission reduction are anyway low under such conditions. On the other hand, based on the experience described above, high emissions might be a comfortable starting position for emitters to negotiate about the future design of the EU ETS. Although the behavior of electricity generators described above, would have been rational and possible there is no proof for it. Nevertheless, these considerations about tactical behavior of market participants illustrate possible difficulties to evaluate the impact of the EU ETS.

In addition there are several other overlapping effects complicating the analysis. There is for example a different time horizon for different mitigation measures. Fuel switching in general is possible in the short run while its extent is limited by installed generation and grid capacity. Therefore, high switching rates need more time. Furthermore, the ETS is not the only reason for emission reduction. Fuel prices also influence the reduction of CO_2. On the one hand the price ratio of coal and gas influences the share of electricity generated from these sources. On the other hand high fuel prices increase incentives for emission reduction by higher efficiency since it also means less expenses for fuel.

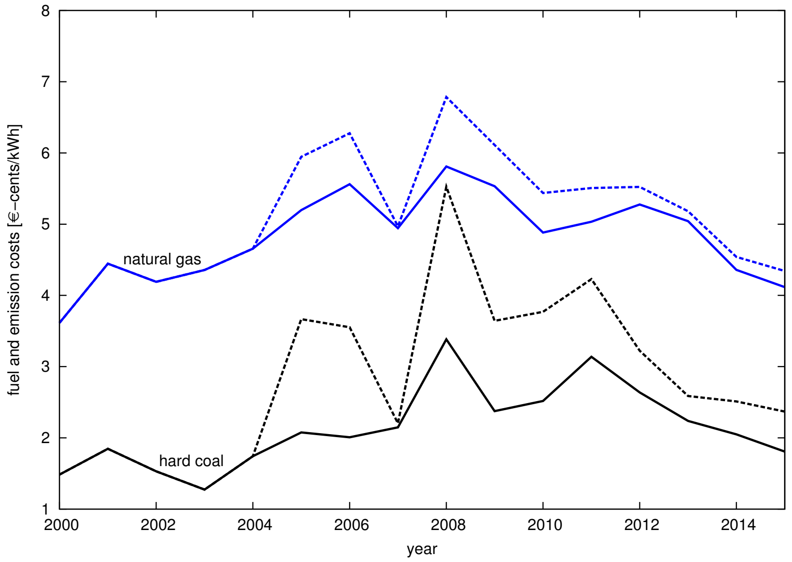

Figure 3: Development of fuel prices for generation of one kWh electricity based on hard coal respectively gas. The solid lines reflect pure fuel prices $\tilde{p}_{i,coal}$ and $\tilde{p}_{i,gas}$ while the dashed lines also consider emission costs induced by the EU ETS yielding $p_{i,coal}$ and $p_{i,gas}$. Prices also consider changes in the degree of efficiency. Own calculations based on Working Group on Energy Balances (2018a),c and Statistics of the Coal Sector (2018).

Taking into account the considerations above, we set up the following approach of a simple linear regression to explain emission intensities e_i of each year i

$$\ln(e_i) = b + a_t \cdot (i - 1999) + a_p \cdot p_{i,ratio} + \epsilon \tag{1}$$

with b as axis intercept, ϵ as error term and $p_{i,ratio}$ corresponding to the price ratio between coal and gas ($p_{i,coal}/p_{i,gas}$).

Prices $p_{i,coal}$ and $p_{i,gas}$ consist of pure fuel prices $\tilde{p}_{i,coal}$ and $\tilde{p}_{i,gas}$ plus a respective surcharge $\Delta p^{ets}_{i,coal}$ and $\Delta p^{ets}_{i,gas}$ stemming from the EU ETS. Fuel prices reflect fuel costs per kilowatt hour generated electricity and thus consider different degrees of efficiency for coal and gas power plants (see Appendix A for details). Hence, the price ratio $p_{i,ratio}$ considers fuel and allowance prices (see Fig. 3).

Since electricity generation faced a radical change after the German reunion in 1990 (Ellerman and Buchner, 2008) we restrain the regression to data beginning in the year 2000. Prices are calculated using data from Working Group on Energy Balances (2018a,c) and Statistics of the Coal Sector (2018) (see Appendix A, Table 6 for results).

3.1 Analysis of the counterfactual scenario without ETS

The results of the empirical analysis based on the linear regression according to Eq. 1 are given in Tables 1 and 2. The adjusted coefficient of determination $\bar{R}^2$ is equal to 0.818. This value is also significantly higher than the coefficient of determination in a model which only considers a_t (R^2=0.766) respectively a_p (R^2=0.505). Eq. 1 provides a satisfactory approach to explain changes in emission intensities. However, data is restricted to only 16 points.

R^2	0.842
$\bar{R}^2$	0.818
F_{emp}	34.74
d	1.74
VIF	1.43

Table 1: General statistical analysis of the linear regression with R^2 as coefficient of determination, $\bar{R}^2$ as adjusted coefficient of determination, F_{emp} as result of the F-test, d as result of the Durbin-Watson statistic and VIF corresponding to the variation inflation factor.

According to the statistical analysis provided in Table 2, in particular the time trend is decisive for the development of the emission intensity ($\hat{a}_t > \hat{a}_p$). Nevertheless, both a_t and a_p lead to significant results for the explanation of changes in emission intensities (see F-test provided in Table 1 and t-test provided in Table 2).

Emission costs induced by the EU ETS, change prices for electricity generation and are thus included in the ratio of prices $p_{i,ratio}$. If emission costs are not considered (using $\tilde{p}_{i,ratio}$ instead of $p_{i,ratio}$) $\bar{R}^2$ decreases to 0.764 which is even slightly lower than R^2 of a model neglecting a_p (see Table 2). Consequently in this case a_p would not significantly contribute to the explanation of changing emission intensities ($p(t_{emp}) =$ 19.35 %). This indicates that the EU ETS has a significant impact on the change of emission intensity. The inclusion of more coefficients (price ratios), due to limited data, does not improve results.

	a_t	a_p	b
	-0.0051	-0.0777	6.7440
$\hat{a}$	-0.695	-0.330	
s	0.0010	0.0310	0.0144
t_{emp}	-5.28	-2.50	
$p(t_{emp})$	0.01%	2.63%	
R^2	0.766	0.505	

Table 2: Statistical analysis of coefficients a_t, a_p, b with $\hat{a}$ as standardized coefficients, s as standard error, t_{emp} as empirical t-value, $p(t_{emp})$ as the respective probability of the t-value and R^2 as coefficient of determination resulting from a correlation test for a_i and a_p separately.

A counterfactual scenario can be constructed using Eq. 1 with the calculated coefficients a_t and a_p but neglecting the impact of the EU ETS on prices. That is using $\tilde{p}_{i,ratio} := \tilde{p}_{i,coal}/\tilde{p}_{i,gas}$ instead of $p_{i,ratio}$. Comparison of real emission intensities with the counterfactual intensities yields a first approach for the impact of the EU ETS on intensities. On the one hand this approach may overestimate the effect of the EU ETS because all changes in intensities which are not explained by Eq. 1 are assigned to the EU ETS. On the other hand the effect of the EU ETS may be underestimated because we implicitly assume that the time trend is not affected by the ETS. However, so far allowance prices of the EU ETS were much lower than 30 €/t (see Fig. 2) which were expected before implementation of the EU ETS (Commission of the European Communities, 2000). Thus, an impact of EU ETS on the long-run time trend is not very likely.

According to our analysis, the time trend leads to a decrease of emission intensity in the electricity sector by 0.5 % each year. The same result Ellerman and Buchner (2008) received for the EU 15 as average for the years 2000 – 2004. They use this value for their counterfactual scenario. In contrast to our approach they do not consider fuel prices. Furthermore, our counterfactual scenario is based on an empirical analysis while they simply use the average of a very short pre-ETS era.

The time trend structurally affects estimated emission reduction assigned to the EU ETS. The stronger the time trend, the lower are remaining emission reductions of the

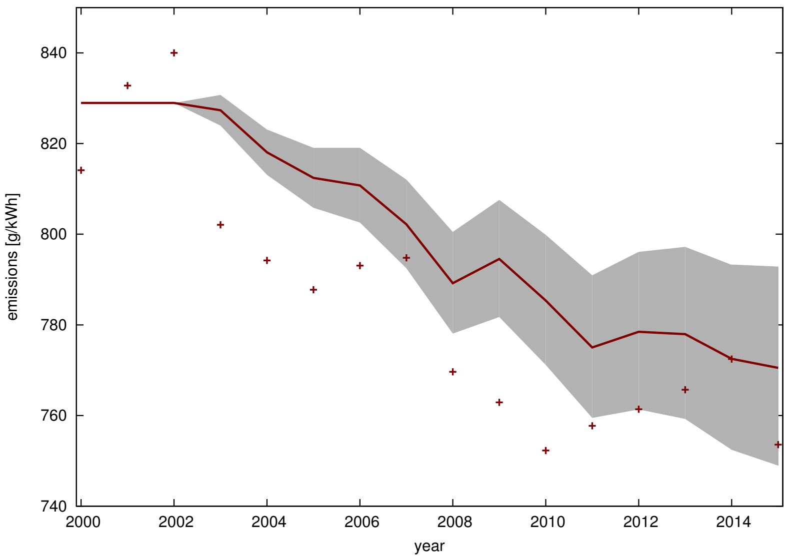

Figure 4: Counterfactual development of emission intensities and real development of emission intensities. The shaded area corresponds to the confidence interval of the time trend. The solid line within the shaded area is the counterfactual scenario using the mean a_t.

EU ETS. The confidence interval with respect to a_t thus gives a reasonable range for changes in emission intensity induced by the EU ETS. The effect of the price ratio, in contrast, does not structurally affect emission intensities because both fuel and allowance prices have an impact on the price ratio. A higher effect of a_p may thus lead to higher or lower values for the counterfactual scenario.

A reasonable counterfactual scenario should consider the confidence interval of a_t to reflect the probable range of counterfactual emission intensities. Since emissions of the first two trading periods were allocated with respect to the average of the years 2000 – 2002 we use the average of these years as common starting point for our counterfactual scenario. That is b is chosen in such way that the calculated average of emission intensities between 2000 – 2002 exactly corresponds to the real value.[3] In Fig. 4 the resulting counterfactual scenario and the real emission intensities are depicted. We see a decreasing trend for both the counterfactual scenario and measured emission intensities. Measured emission intensities are mainly below the counterfactual emission intensities which indicates reduced emissions by the EU ETS.

3.2 Calculation of emission abatement induced by the EU ETS

According to our empirical approach, the difference between counterfactual and measured emission intensities corresponds to the estimated change of emission intensity

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[3] b is nevertheless always within its confidence interval.

induced by the EU ETS. Results are given in Table 3. Positive values indicate a reduction of emission intensity while negative values mean an increasing intensity (negative reduction). Although at first sight it might seem absurd that the ETS could lead to higher emission intensity it cannot be excluded for all years of observation. Lobbying and tactical behavior might incentivize higher emission intensities to convince the regulator of a less strict cap in the future. Since we cannot estimate the effect of tactical behavior we put negative values into brackets (see Table 3). The product of intensity change and ETS-influenced electricity generation $S_{ets,i}$ of the respective year i (see Appendix A, Table 5) yields an estimate for the change in emissions which is automatically corrected for demand side effects (see Table 3).

	intensity reduction [g/kWh]			CO_2 reduction [Mt]		
year	lower limit	mean	upper limit	lower limit	mean	upper limit
2005	18.1	24.7	31.3	7.5	10.2	13.0
2006	9.5	17.7	26.0	4.0	7.4	10.9
2007	[-2.3]	7.4	17.3	[-1.0]	3.2	7.5
2008	8.4	19.5	30.9	3.6	8.2	13.0
2009	18.8	31.6	44.7	7.3	12.2	17.2
2010	18.9	33.1	47.6	7.7	13.5	19.5
2011	1.7	17.3	33.2	0.7	6.9	13.3
2012	[-0.1]	17.1	34.7	0.0	7.0	14.3
2013	[-6.4]	12.3	31.5	[-2.7]	5.1	13.1
2014	[-20.0]	0.1	20.8	[-7.9]	0.0	8.2
2015	[-4.6]	16.9	39.2	[-1.8]	6.6	15.4

Table 3: CO_2 and intensity reduction in the German electricity sector induced by the ETS. Negative values (in brackets) mean an intensity respectively CO_2 increase compared to the counterfactual scenario. This might happen due to tactical behavior.

For the first trading period from 2005 – 2007 our approach yields an emission reduction between 10.5 and 31.4 Mt CO_2. Ellerman *et al.* (2010) find for the same period an emission reduction of about 34.5 Mt CO_2 in the German electricity sector which is a bit higher than our highest estimate. However, Ellerman *et al.* (2010) do not consider the effect of fuel prices and they do not exclude subsidized renewable electricity generation from their data. Emission reduction induced by the promotion of renewable energy is also assigned to the EU ETS in their approach. Compared to 2004 the increase of electricity generated by RES is moderate in 2005 but rather high in 2006 and 2007 (see Schäfer, 2018). This might explain why Ellerman *et al.* (2010) see a higher emission reduction in 2006 when compared to 2005 although the averaged allowance price is slightly lower in 2006. This leads to a probable overestimation of emission reduction assigned to the ETS by Ellerman *et al.* (2010) while our approach avoids this.

The change of emission intensity in relation to the average emission intensity of the base period (2000 – 2002) is depicted in Fig. 5. Using the mean value of the counterfactual scenario the reduction of emission intensity was on average 2.0 % during the first trading period, followed by 2.9 % in the second trading period and 1.2 % in the first three years of the third trading period. Between 2005 and 2015 the maximal decrease of intensity ranged between 2.3 % (lower limit) and 5.7 % (upper limit) of total emissions. Calculating the reduction of emission intensity in relation to the respective counterfactual emission intensity instead of the base period yields a maximal intensity reduction between 2.4 % and 5.9 %. This maximum was already reached in 2010 (see Fig. 5).

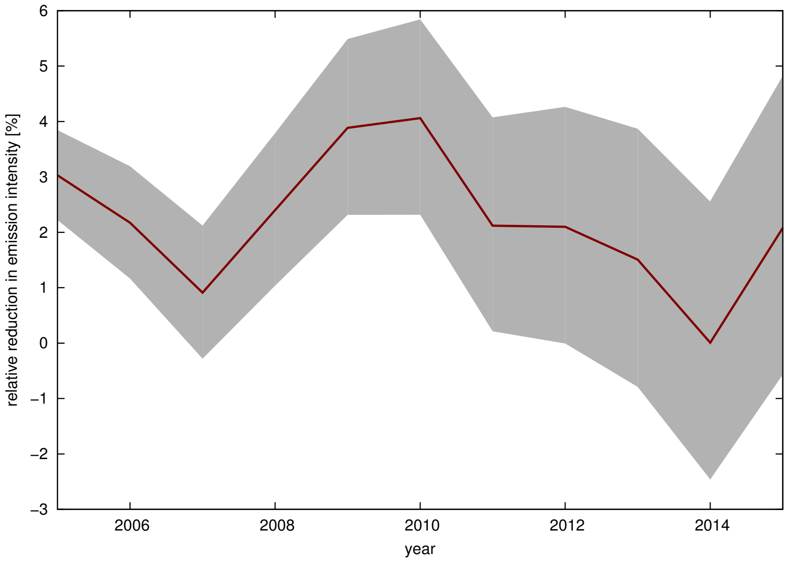

Figure 5: Reduction of emission intensity induced by the EU ETS in relation to the counterfactual intensity. The shaded area considers the confidence interval of the time trend. The solid line within the shaded area uses the mean a_i. Positive values correspond to a reduction in emission intensity while negative values mean an increase.

The revised German NAP for the second trading period intended, with respect to the electricity sector, an overall average emission reduction of around 14 % at the minimum when compared to the base period (see Section 2 for details). According to data from Working Group on Energy Balances (2018b), Federal Environment Agency (2018), Statistics of the Coal Sector (2018) the average emission reduction was only 5.9 % (see Schäfer, 2018). Neglecting demand side effects and thus looking at emission intensities instead yields an average reduction of 8.2 % for the second trading period when compared to the average of the base period (see Table 5 in Appendix A). The EU ETS contributed a decrease between 1.2 % (lower limit) and 4.6 % (upper limit). For the first three years of the third trading period emission intensity is only reduced by 7.8 % in comparison to the base period which means an increase of 0.4 % when compared to the average of the second trading period. The European Commission instead intended, starting from 2010, an emission reduction over all sectors of annually 1.74 % with respect to the average of the second trading period (see Section 2).

The promotion of RES which was carried out simultaneously to the EU ETS, led to a significantly higher decrease in emissions. According to Schäfer (2018), CO_2 reduction induced by the promotion of RES increased from 29.1 Mt before the start of the EU ETS in 2004 to 59.3 Mt in 2010 and 116.6 Mt in 2015. This yields additional emission savings of 30.2 Mt in 2010 and 87.5 Mt in 2015 while the EU ETS resulted in a reduction between 7.7 and 19.5 Mt in the most successful year 2010 and -1.8 to 15.4 Mt in 2015. Subsidized RES thus contributed at least 50 % more to emission reduction in the German electricity sector in 2010 and at least 460 % in 2015 than the EU ETS. Although the comparison of EU ETS and renewables neglects subsidies which were necessary to achieve the abatement by RES it gives an impression about what was possible with respect to emission reduction between 2005 and 2015.

Overall we find a limited success of the EU ETS with respect to emission reduction in the German electricity sector. Expectations stipulated before the second and third trading period have not been fulfilled. The highest decrease of CO_2 when compared to the counterfactual scenario appeared already in 2010. The EU ETS has not achieved any further emission reduction since 2010.

4 Readjustment of the EU ETS

Newell and Pizer (2008) provide a model which can be used to figure out if an absolute or an intensity-based cap is more promising to maximize welfare. Sue Wing *et al.* (2009) use a similar but simpler approach. They neglect social benefits and focus on abatement costs only. Their aim is to minimize variance from expectations leading to lowest costs. In the following we apply both approaches to data from the German electricity sector.

4.1 Analysis of empirical data

Sue Wing *et al.* (2009) use data for emission and GDP of a decade for application of their model and assume a time lag of five years. That means they use data from 2001 till 2010 to find out if an intensity-based cap is superior when compared to an absolute cap in 2015. We follow their approach with two modifications.

First, a time lag of three years seems more adequate because of the good data situation in Germany. Second, we do not assess emissions of the electricity sector in relation to GDP but in relation to its output in the sphere of the EU ETS.[4] That is we use the emission factor as intensity-based quantity. This allows the necessary calculation of $\xi = \frac{\nu(S_{ets})}{\nu(E)\rho_{ES}}$ which is the decisive parameter of our analysis. $\nu(S_{ets})$ and $\nu(E)$ are the variation coefficients of emissions E and electricity output in the sphere of the EU ETS S_{ets}. ρ_{ES} is their correlation (see Fig. 6 for results).

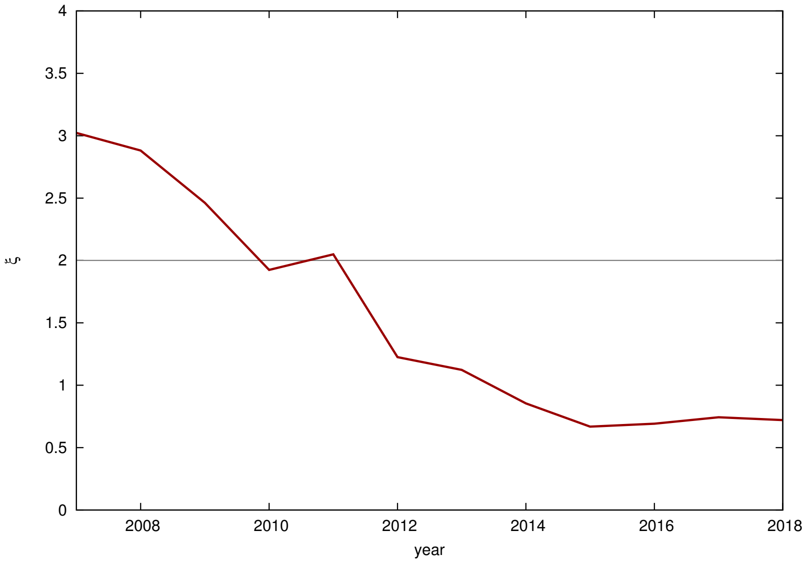

Figure 6: Calculation of $\xi = \frac{\nu(S_{ets})}{\nu(E)\rho_{ES}}$ for an intensity-based cap in the German electricity sector. $\nu(S_{ets})$ and $\nu(E)$ are the variation coefficients of emissions E and electricity output in the sphere of the EU ETS S_{ets}. According to Sue Wing *et al.* (2009); Newell and Pizer (2008), intensity-based quantities are preferred to fixed quantities if ξ is lower than 2. Note the time lag of three years. The estimation for 2007 underlies data from 1995 – 2004.

Under the described use of data (ten years, time lag of three years) the approach of Newell and Pizer (2008) delivers the same results within the accuracy of one decimal digit. This is not surprising since marginal damage of emissions with respect to annual data is almost flat (Newell and Pizer, 2003). For $\xi < 2$ an intensity-based cap is superior to an absolute cap while the opposite is true for $\xi > 2$. According to Newell and Pizer (2008), values between 1 and 2 mean an over-adjustment by an intensity-based regulation while values below 1 indicate under-adjustment when compared to the optimum.

As discussed in Section 3 Germany faced major transitions after its reunion in the 1990s. Estimates for ξ which are based on data before 2000 should be treated with caution. The calculations show a decrease of ξ and at least since 2012 a high preference of intensity-based quantities over absolute quantities for electricity generation in Germany (see Fig. 6). Since results may be different in non-electricity sectors intensity-based quantities may be applied for electricity generation only. Schmidt

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[4] As discussed in Section 3 we subtract electricity generation by nuclear power plants and promoted RES from total electricity output to receive electricity generation in the sphere of the EU ETS.

et al. (2008) for example also suggest a sectoral approach for an ETS whereas they investigate the interaction between developing and industrialized countries.

4.2 Introduction of a unilateral flexible cap

Setting a reasonable objective of absolute emission reduction for year i means to implicitly consider a certain expectation about the electricity output $S^e_{ets,i}$ which is in the sphere of the EU ETS (see for example European Commission, 2006). This objective is translated into a maximal number of allowances $E^{'}_i$. Thus, ex-ante there is a fixed relation between the absolute number of allowances $E^{'}_i$ and the corresponding emission intensity $e^{'}_i$ as respective intensity-based objective

$$e^{'}_i = \frac{E^{'}_i}{S^e_{ets,i}}. \tag{2}$$

Demand side effects as for example the promotion of renewable energy or business cycles may lead to a deviation of actual ETS-affected electricity generation $S_{ets,i}$ from the expected level

$$\Delta S_{ets,i} = S^e_{ets,i} - S_{ets,i}. \tag{3}$$

This has an effect on absolute emissions while it does not affect the emission factor $e^{'}_i$. The emission intensity can thus be used to calculate the difference in emission certificates arising from the deviation of expected electricity generation

$$\Delta E^{'}_i = \Delta S_{ets,i} e^{'}_i. \tag{4}$$

An intensity-based cap corrects demand side effects. However, in contrast to an absolute cap, it shows uncertainty to reach an absolute objective. This disadvantage is avoided if an intensity-based cap is defined as secondary objective in addition to an absolute cap which serves as primary objective. The primary objective effectuates that emissions are lower or equal to the number of certificates $E^{'}_i$. The secondary objective (emission intensity should be lower or equal to $e^{'}_i$) is respected only if the primary objective is fulfilled. This means the intensity-based cap is only binding if electricity generation is lower than expected. For an electricity generation above expectation there is no adjustment. The result is a unilateral flexible cap.

There are several reasons which argue for the suggested combination of absolute and intensity-based emission cap. On the one hand there is a broad agreement to limit global warming to a maximum of 2 °C of the preindustrial temperature level which requires an absolute cap in emissions. Some authors see the two degrees as threshold value whose excess leads to catastrophe (see Jaeger and Jaeger, 2011, for an overview). Despite all critique the two degrees are certainly the most prominent lowest common denominator in international climate policy. This is already a high value in itself (Jaeger and Jaeger, 2011).

On the other hand an intensity-based emission cap increases the security of investments in emission reduction because it decouples the EU ETS from demand side effects. This keeps the pressure on emission reduction which points into the same direction like UK's carbon price floor.[5] An intensity-based emission cap also avoids efficiency losses if RES are promoted simultaneously to the EU ETS. The unilaterality of the flexible cap is a desired feature because the EU ETS already provides mechanisms to limit the certificate price in case of a scarcity of certificates (European Parliament and Council of the EU, 2009). In addition there is still the possibility to count international credits (CERs, ERUs) towards emissions of the EU ETS which counteracts high prices.

The idea of a unilateral flexible cap is to subtract the amount of excessive emission certificates, which occurred in year i from the intended amount of certificates to be auctioned in year $i+1$. In contrast, if in year i there is a higher electricity generation than expected yielding to a scarcity of emission certificates, the number of missing certificates will be balanced, only if there have been excessive certificates before year i or there will be excessive certificates after year i within the same trading period. The unilateral flexible cap has similarities to the dual-intensity targets suggested by Kim and Baumert (2002).

These considerations yield an adjusted number of certificates

$$\tilde{E}_i^{'} = E_i^{'} - R_{i-1} \tag{5}$$

with

$$R_i = \max\left\{0, \sum_{j=1}^{i}\left(\Delta E_j^{'} + \tilde{E}_j^{'} - E_j^{'}\right)\right\} \tag{6}$$

and

$$R_{i-1} := 0 \qquad \forall i \leq i_{start}. \tag{7}$$

i_{start} is the first year the unilateral flexible cap is applied. R_i is a reserve which is fed by excessive allowances. There are similarities to the general idea of the market stability reserve which was introduced by the European Parliament and Council (2015). However, the mechanism how certificates enter the reserve and how they are deleted

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[5] UK introduced a carbon price floor to guarantee a minimum price for emissions. The carbon price floor consists of the allowance price of the EU ETS plus a variable surcharge which in total yields the minimum price.

is different

It is important to note, that the adjustment takes place according to a predetermined and therefore, predictable mechanism for market participants. Production declines are made neutral to allowance prices regardless if they are caused by economic development, the use of additional renewable energy or a warm winter. The fluctuations of the certificate price are expected to weaken significantly reducing uncertainty for investments in CO_2 abatement accordingly. This should lead to a stabilization of investment activities.

4.3 Ex-post evaluation of the impact of a unilateral flexible cap

After the theoretical considerations in the preceding section we want to evaluate the impact of the suggested unilateral emission cap on the number of allowances. Since the first trading period was seen as trial period (e.g. Kollmuss *et al.*, 2010, p. 68) we assume the unilateral emission cap was introduced before the start of the second trading period in 2008. This allows to carry out an ex-post-analysis to find out how the number of allowances would have developed if a unilateral flexible emission cap had been introduced.

As discussed in Section 4.1 emission intensity serves as suitable intensity-based cap. According to Eq. 2, emission intensity is the ratio between the number of allowances in the electricity sector and expected electricity generation in the sphere of the EU ETS ($S^e_{ets,i}$). We need reliable data for both the number of allowances and the expected electricity generation before the start of the second trading period to evaluate the effect of a unilateral flexible cap ex post.

The number of allowances was determined in NAPs (see Section 2 for details). There are two peculiarities which need to be considered for Germany. First, the revised German NAP planned a reserve for market entries of new installations while the final shut down of installations should reduce the number of allowances (Federal Ministry for the Environment, 2007). The planned number of certificates does therefore not exactly correspond to issued (auctioned and freely allocated) allowances. Second, the German NAP planned free allocation of certificates for the ETS-underlying industry while necessary certificates for the power sector were partially auctioned off. Considering these effects the intended CO_2 budget for the power sector can be determined by subtracting freely allocated allowances for the industry from the total number of issued certificates using data from European Environment Agency (2018).

The power sector does not only consist of electricity generation but also includes thermal power plants for district heating. In 2005, which served as reference year for the determination of the emission cap of the second trading period (European Commission, 2006), the emission share of electricity generation on the power sector was about 0.9 (see Schäfer, 2018). Thus, we assume this share to calculate the emission budget of electricity generation from the CO_2 budget of the complete power sector.

In the third trading period there are no national budgets anymore. Since the EU-wide emission cap is derived from the average of allowances in the second trading period we can calculate a respective theoretical budget for the third trading period according to the same mechanism (see last paragraph in Section 2). The results are given in Table 4.

year i	$E_i^{'}$ [Mt]	$S_{ets,i}^e$ [TWh]	$e_i^{'}$ [g/kWh]	$S_{ets,i}$ [TWh]	$\Delta S_{ets,i}$ [TWh]	$\Delta E_i^{'}$ [Mt]	R_i [Mt]	$\tilde{E}_i^{'}$ [Mt]
2008	267.6	439.6	608.7	420.8	18.8	11.5	11.5	267.6
2009	262.1	439.6	596.3	385.7	53.9	32.1	32.1	250.6
2010	267.6	439.6	608.7	409.6	30.0	18.3	18.3	235.5
2011	267.7	439.6	608.9	401.1	38.5	23.5	23.5	249.4
2012	294.5	439.6	669.8	410.8	28.8	19.3	19.3	271.0
2013	257.7	405.2	635.9	414.7	-9.5	-6.0	0.0	238.4
2014	253.0	403.8	626.5	392.7	11.1	7.0	0.9	253.0
2015	248.2	402.3	617.0	392.4	9.9	6.1	6.1	247.3
sum	**2,118.3**					**111.7**		**2,012.8**

Table 4: Ex-post evaluation of the EU ETS assuming a unilateral cap for the German electricity sector as described in Section 4. $E_i^{'}$ corresponds to the emission budget of the ETS which is calculated based on European Environment Agency (2018), Schäfer (2018), European Commission (2010). The expected electricity generation $S_{ets,i}^e$ is calculated on the basis of Capros and Mantzos (2006), Capros *et al.* (2010), Working Group on Energy Balances (2018b). The ratio of $E_i^{'}$ and $S_{ets,i}^e$ yields the emission intensity $e_i^{'}$ while the actual electricity generation in the sphere of the ETS $S_{ets,i}$ is based on Working Group on Energy Balances (2018b), Information Platform of the German Transmission System Operators (2018). The deviation from expected electricity generation $\Delta S_{ets,i}$, the difference in allowances $\Delta E_i^{'}$, the reserve R_i and the adjusted number of allowances $\tilde{E}_i^{'}$ are calculated according to Eq. 3 – 5.

The European Commission rejected the German NAP for the second trading period because assumptions about economic growth and technological potential for emission reduction were not considered (European Commission, 2006). In this context the Commission pointed to the PRIMES model (Capros and Mantzos, 2006) "*as the most accurate and reliable estimations of both GDP growth and carbon intensity improvement rates*" (European Commission, 2006, p. 5). The Commission considered "*2010 to constitute a representative average of the relevant five-year period from 2008 to 2012*" (European Commission, 2006, p. 5). Since 2005 served as reference year, the Commission used estimates about economic growth and the technological potential for emission reduction for the period from 2005 – 2010 to set up the cap for the second trading period. For an estimate of expected ETS-affected electricity generation in 2010 the regulator could have followed the same path as the Commission did in 2006 to estimate economic growth and emission intensity.

According to Capros and Mantzos (2006), thermal-based electricity generation (including biomass) in Germany should increase by 5.8 %[6] from 2005 until 2010. In the same period electricity generation from wind and hydro power plants was expected to increase by almost 50 % while a decrease of electricity from nuclear power plants was expected which reflects the German decision about the nuclear phase-out.

As discussed in Section 3 total electricity generation minus electricity which is generated by nuclear power plants and subsidized RES corresponds to total electricity output which may be affected by the ETS.[7] According to Working Group on Energy Balances (2018b) and Information Platform of the German Transmission System Operators (2018), this electricity output amounted to 415.5 TWh (97.2 % from thermal power plants) in 2005. This information was already available in 2006. Following the approach of the European Commission (2006) for GDP to combine data of the reference year 2005 with the estimated growth rate we find for expected electricity generation $S^e_{2010} = 415.5 \text{ TWh} \cdot 1.0579 = 439.6 \text{ TWh}$ (see Table 4).

The same approach as described for the second trading period could be applied for the third trading period referring to the updated version of the PRIMES model (Capros *et al.*, 2010). According to this source, thermal-based electricity generation (including biomass) in Germany should decrease from 2010 until 2015 by 1.8 %[8]. For 2010 as new reference year the ETS-relevant electricity generation amounted to 409.6 TWh (Working Group on Energy Balances, 2018b). This yields for the first year of the third trading period $S^e_{2013} = 409.6 \text{ TWh} \cdot (1 - (1 - 0.9822)/5 \cdot 3) = 405.2 \text{ TWh}$. The expected electricity supply for the following years can be calculated following the same approach (see Table 4).

The application of a unilateral flexible cap instead of an absolute cap would have reduced the number of emission allowances for the second trading period by 104.7 Mt. That corresponds to 7.7 % of totally issued certificates for the German electricity sector (see Table 4). Neuhoff and Schopp (2013) estimate excessive allowances caused by the financial and economic crisis to 650 million within the EU. This corresponds, according to European Environment Agency (2018), to 6.2 % of totally issued certificates in trading period two. Assuming a similar impact of the crisis among the EU this suggests a significant reduction of excessive allowances by the unilateral flexible cap in Germany.

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[6] 390,045/368,682=1.0579 (Capros and Mantzos, 2006, p. 102)

[7] An alternative approach would be to include only electricity generated by power plants which are underlying the ETS.

[8] 414,780/422,310=0.9822 (Capros *et al.*, 2010, p. 87)

Nevertheless, the impact of a unilateral flexible cap on the EU-level is left open for further research since our analysis is restricted to the German electricity sector.

5 Conclusions

We analyze data from the German electricity sector with a simple statistical model. This allows to estimate the success of the EU ETS in terms of emission reduction. Results show that ETS-induced CO_2 mitigation has been relatively low so far. The maximal emission reduction was already reached in 2010 amounting to a range between two and six percent of total emissions when compared to a counterfactual scenario without ETS. In the proceeding years there has been no additional emission reduction with respect to the counterfactual scenario. Results do not comply with expectations for the EU ETS.

Our estimations are roughly in line with other publications but show several refinements. For the first trading period we estimate an emission reduction between 10.5 and 31.4 Mt CO_2. This range is slightly lower than the result of Ellerman *et al.* (2010) who find 34.5 Mt. However, our model, in contrast to Ellerman *et al.* (2010), considers the effect of fuel prices and CO_2 reduction by promoted RES. Thus, the range presented in this chapter seems more realistic.

There is a broad consensus that the detected limited success of the EU ETS has been caused by excessive allowances. While there are easy possibilities to limit excessive allowances on the supply side by simple direct regulation (see e.g. European Commission, 2012b) this does not apply for the demand side. We develop a mechanism which uses an intensity-based cap in addition to the absolute cap to tackle this problem.

In a first step we study the performance of an intensity-based emission cap applying data of the German electricity market to the (similar) theories of Newell and Pizer (2008) and Sue Wing *et al.* (2009). Results show the superiority of an intensity-based cap when compared to an absolute cap. In combination with an absolute cap the compliance to objectives of absolute emission reduction is guaranteed, too. The intensity-based cap is thus used to induce a reduction of allowances in the event of excessive allowances while it will not lead to an increase of allowances. The resulting unilateral flexible cap eliminates excessive allowances because of demand side effects. The suggested cap absorbs for instance the impact of a promotion of RES on the EU ETS. This is a decisive step to decouple the promotion of RES and the ETS which are overlapping regulations.

In an ex-post analysis we study the impact of a unilateral flexible cap assuming it would have been introduced to the German electricity sector before the start of the second trading period. According to our model, the regulator states an intensity-based cap before the start of each trading period which is in analogy to the absolute cap. Therefore, he or she can only use information which already available before the respective trading period starts. With this approach we identify for the second trading period, which took place between 2008 and 2012 and thus covers the financial and economic crisis, a decrease of 104.7 Mt. This corresponds to a share of 7.7 % on issued certificates.

The unilateral flexible cap is advantageous when compared to the market stability reserve introduced by the EU in 2015. While we suggest a clear mechanism for an adjustment of the absolute emission cap the EU's market stability reserve works with a threshold value. This threshold value prevents a total elimination of demand side effects on the EU ETS and it is vulnerable for lobbying. Since introduction of the market stability reserve the threshold value was already changed. The market stability reserve also suffers from lacking a clear procedure to delete excessive allowances. So far EU Member States only agreed on a single action in 2023. This will require additional interventions. However, frequent interventions reduce the credibility of the EU ETS among participants.

With respect to the empirical part of this section a broader database would be a benefit. This would allow refinements of the statistical approach to get a better estimation for the impact of the EU ETS on the German electricity sector. While we have focused on Germany in this chapter further research should also evaluate the applicability of an intensity-based cap to other EU Member States.

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A Empirical data and calculations

We use the annually published energy balances (Working Group on Energy Balances, 2018a) as basis to calculate CO_2 emissions of the German electricity sector. These balances reveal the primary energy used for electricity generation from different fossil sources (coal, lignite, gas etc.).

Together with the emission factors (Federal Environment Agency, 2018) this allows to calculate CO_2 emissions E_i for year i. Calculations for emissions from lignite-fired power plants additionally need some refinement according to the annual lignite statistics (Statistics of the Coal Sector, 2018). Based on Schäfer (2018) we can assume that all fossil-based power plants are underlying the EU ETS.

The annual electricity output specified by source is provided by Working Group on Energy Balances (2018b). Information about electricity which is generated by subsidized RES is available at Information Platform of the German Transmission System Operators (2018) and Wagner (2000). This allows to calculate the electricity output $S_{ets,i}$ which is in the sphere of the EU ETS.[9] The emission intensity e_i is the ratio of E_i and $S_{ets,i}$ (see Table 5 for data and calculations).

year i	$E_i^{[1],[2],[3]}$[kt]	$S_{ets,i}$[4][TWh]	e_i[g/kWh]
2000	319,871	392.91	814.1
2001	330,582	396.96	832.8
2002	333,422	396.93	840.0
2003	333,172	415.38	802.1
2004	327,128	411.89	794.2
2005	327,339	415.53	787.8
2006	333,613	420.65	793.1
2007	344,211	433.09	794.8
2008	323,829	420.75	769.6
2009	294,283	385.74	762.9
2010	308,115	409.57	752.3
2011	303,903	401.06	757.7
2012	312,756	410.77	761.4
2013	317,535	414.71	765.7
2014	303,319	392.67	772.5
2015	295,685	392.37	753.6

Table 5: CO_2 emissions E_i and electricity output $S_{ets,i}$ which is in the sphere of the ETS: Data based on on [1] Working Group on Energy Balances (2018a), [2] Federal Environment Agency (2018), [3] Statistics of the Coal Sector (2018), [4] Working Group on Energy Balances (2018b). The emission factor e_i is equal to the ratio of E_i and S_i^{ets}.

Fuel prices are taken from Statistics of the Coal Sector (2018). The degree of efficiency

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[9] The electricity output in the sphere of the EU ETS corresponds to the gross electricity output minus nuclear-based electricity generation and electricity from subsidized RES.

can be calculated dividing generated electricity given in Working Group on Energy Balances (2018b) by used primary energy given in Working Group on Energy Balances (2018a). This allows to calculate averaged fuel prices per generated kilowatt hour.

The price for emission allowances for 2005 is, due to lack of other data, until the middle of September based on forward prices. Afterwards the average price of the respective December Futures of the Intercontinental Exchange (ICE) are used (German Emissions Trading Authority, 2009, 2013; Intercontinental Exchange, 2018). Considering the specific emission intensities and efficiency of coal-fired and gas-fired power plants emission costs per generated kilowatt hour can be calculated (see Table 6).

year i	$p_{i,gas}^{[1],[2],[3}$ [€-Cents/kWh]	$\Delta p_{i,gas}^{ets[4],[5],[6]}$ [€-Cents/kWh]	$p_{i,coal}^{[1],[2],[3]}$ [€-Cents/kWh]	$\Delta p_{i,coal}^{ets[4],[5],[6]}$ [€-Cents/kWh]
2000	1.48		3.61	
2001	1.85		4.45	
2002	1.53		4.19	
2003	1.27		4.36	
2004	1.74		4.66	
2005	3.67	1.59	5.95	0.75
2006	3.55	1.55	6.28	0.71
2007	2.20	0.06	4.97	0.03
2008	5.53	2.14	6.78	0.97
2009	3.64	1.27	6.11	0.58
2010	3.77	1.25	5.44	0.56
2011	4.23	1.09	5.51	0.47
2012	3.22	0.58	5.52	0.25
2013	2.59	0.35	5.18	0.14
2014	2.51	0.46	4.54	0.18
2015	2.37	0.56	4.34	0.23

Table 6: Fuel prices $p_{i,gas}, p_{i,coal}$ and allowance prices $\Delta p_{i,gas}^{ets}, p_{i,coal}^{ets}$: Own calculations are based on data from [1] Working Group on Energy Balances (2018a), [2] Working Group on Energy Balances (2018b), [3] Statistics of the Coal Sector (2018), [4] German Emissions Trading Authority (2009), [5] German Emissions Trading Authority (2013), [6] Intercontinental Exchange (2018)