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Effective Promotion of Renewable Energy in the Presence of an Emissions Trading System

Analysis of the Success of ETS and Promotion of Renewable Energy as overlapping regulations in Germany – adjustment of the ETS

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Abstract

This paper contributes to the literature of overlapping regulations as we introduce a model, which gives insights in an effective combination of the EU emissions trading system (ETS) and the promotion of renewable energy within the electricity sector. Under consideration of EU long term objectives in CO_2 mitigation we evaluate the efficient share of renewable energy. Hence, we give rise to the question, if the actual amount of renewable energy production already exceeds this share making a stop or at least a modification of its promotion necessary. Our approach proves to be robust to a change of pattern of marginal abatement costs (MAC), while resulting variances can be narrowed down and quantified. For its application to empirical data, we develop a method to evaluate the performance of the ETS and the promotion of renewable energy. On that basis we suggest modifications of the ETS to uncouple the certificate price from economical fluctuations and the development of renewable energy leading to their better combination and stronger mitigation incentives. For Germany it turns out, that the electricity generation of renewables has not exceeded its optimal share yet, while data is restricted due to low mitigation incentives set by the ETS. Therefore both the suggested improvement of the ETS and the monitoring of the development of renewable energy, referred to our model, is strongly recommended.

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1 Introduction

To mitigate anthropogenic climate change, the EU has agreed to a long-term reduction of greenhouse gas emissions by an average of 80 – 95 % by 2050 with respect to the 1990 reference year (European Council, 2009). Since the ETS with its progressive scarcity of tradable permits has been introduced, the expansion of renewable energy throughout EU Member States is encouraged in many different ways. While both strategies are aimed at the reduction of greenhouse gas emissions, they are very different in terms of their current and future MAC. The current intermediate objectives of the ETS only induce a partial internalization of CO_2 costs. This leads to lower MAC compared to renewable energy, where abatement costs are defined as additional costs compared to fossil electricity generation. This MAC gap makes the ETS currently result in no incentive for substitution of fossil fuels by renewables. Therefore a separate view on the promotion of renewable energy and the ETS, especially with respect to the development of their MAC is reasonable. The result is a separate curve MAC_r for renewable energy and MAC_{ets} for emission reductions by the ETS.

The MAC gap will vanish with a tightening of the emissions cap and the subsequent rising of MAC_{ets}, which ultimately will lead to the partial substitution of fossil fuels, just as a consequence to physical reality in connection with the long-run objectives. Within the fossil sector, emission reductions on the production side, can only be achieved by increasing efficiency and shift to low-emission fossil fuels (e.g. natural gas). Since the combustion of a given quantity of a particular fossil fuel is always associated with a fixed amount of CO_2 emissions, the energy content of this particular quantity defines the upper limit of possible CO_2 savings. Gaining more energy than saved in a given quantity of fuel is impossible[1]. These physical facts yield two results. Firstly MAC_{ets} and MAC_r have an intersection point defining MAC parity. Secondly it is reasonable, that MAC_r is less increasing with rising mitigation than MAC_{ets}, because the huge potential of renewables exceeds the demand by far and hence results in no such limitations as described for the fossil sector. Due to the empirically verifiable learning effects (von Hirschhausen *et al.*, 2013), a decreasing MAC is also realistic. But for learning effects only power generation costs are regarded as important, while in particular the costs of the integration of renewable energy into the existing fleet of power plants; e.g. by necessary storage technologies, have to be taken into account. Therefore slightly increasing MAC may be justified as well.

These two results make the long-term use of the ETS as an exclusive climate policy lead to partial substitution of fossil fuels by renewable energy sources as

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[1] Only the technique of carbon capture and storage (CCS) could break this relation. However, in spite of great financial incentives, only a few demonstration plants have been built, in which CCS almost never comes for use in power generation (Global CCS Institute, 2014). The previous hope in this technique has not been satisfied yet (European Commission, 2013). The MAC of CCS technology is suggested in the field of renewable energy anyway (von Hirschhausen *et al.*, 2013, p. 80). That is why the use of this "bridging technology" seems to be less realistic for electricity generation in comparison to the avoidance of process emissions, because there are virtually no other mitigation options (Viebahn *et al.*, 2007).

soon as the MAC parity is reached. Consequently, there would be a sequential use of mitigation strategies, eventually using renewable energy. For this reason, there is a common belief that the pricing of CO_2, for example by the ETS, is a sufficient climate policy (Nordhaus, 2009). Although this strategy change will not happen suddenly, the emission level of the MAC parity may be called the turning point of mitigation strategies. It splits total emissions into two parts and thus shows the share of emissions, which should be mitigated within the fossil sector on the one hand and with renewable energy on the other hand minimizing the total abatement costs. While many studies point out reasons beyond the mitigation of CO_2 emissions to promote renewable energy (del Río González, 2007), within the field of emissions mitigation it is often only seen as a start-up investment and justified with the expected learning effects (Edenhofer *et al.*, 2012).

However, another good reason for the promotion of renewable energy is the expansion of the necessary transformation process over a longer period of time. The faster the conversion to renewable energy needed, the stronger the pressure to the existing fleet of power stations will occur, which will increase the losses of invested capital in those power plants. This increases the risk of a technological lock in and makes the enforcement of emission targets more difficult. Moreover, a simultaneous use of both mitigation strategies will expand the demand for renewable energy plants to a longer period of adjustment and counteract the overheating of markets with correspondingly high prices. Additionally, learning effects can therefore be better lifted. The current stage of development of renewable energy in Germany demonstrates, that some problems (e.g. grid and storage technology) only occur during the transformation process. Hence, a faster transformation uses more technology in its infancy finally causing higher costs. As a result of long climatic impact of CO_2; which goes far beyond the long-term EU's time target of year 2050 (Houghton *et al.*, 1996), the cumulative emissions are crucial for a performance mitigation of climate change. Therefore a stronger early emissions reduction allows a less stringent final objective.

With the acknowledgement that renewable energy has to replace some of the fossil fuels to achieve the long-term goal anyway, the simultaneous use of strategies has significant advantages if only the same share of emissions are avoided by renewables, as it would have been in the case of the sequential operation. This presupposes knowing the turning point of the strategies or at least, if the current share of CO_2 mitigation by renewables already exceeds the optimal long-run share and thus their promotion should be modified or even stopped. Although this is just the intersection of the two MAC functions, this is fraught of high uncertainty because of the many unknowns, especially with regard to the future development. Therefore in Section 3 we develop another method in which the expected errors are small and can be quantified. The assessment of the model is made on the national level, such that for Germany we discuss whether the promotion of renewable energy has exceeded the efficient share yet and violates the path of minimum costs. Additionally we develop an evaluation indicator for the success of the promotion of renewable energy and the ETS in terms of CO_2 mitigation. This allows an adjustment of the ETS to decouple its price from the development of economy and renewables.

2 Evaluation of Germany's main environmental policy instruments to reduce CO_2 emissions

A detailed analysis of the ETS and the promotion of renewable energy with focus on Germany is given in this chapter. This enables us to find realistic indicators to evaluate the success of both policy instruments (see Sections 2.2, 2.5) and to make a suggestion for the improvement of the ETS (see. Section 2.3). This allows a realistic as possible modeling of the theoretical framework derived in Section 3.

2.1 The ETS in the electricity sector

Emissions trading has been faced serious problems since its establishment in the EU by Directive 2003/87/EC. The German emissions cap of the first trading period provided a reduction of 2.91 % compared to the emissions of the base period. The target was set as an intermediate step for the goals of 2012, stipulated in the Kyoto Protocol. After adjusting for a number of special rules (early action, reserve for new installations etc.) the actual reduction was only 0.4 % (Federal Ministry for the Environment, 2004). In retrospect, it turned out the relied database was wrong, so that even without considering the special rules the number of annual certificates issued exceeded the annual emissions of the base period to 0.8 % (Federal Ministry for the Environment, 2006). A scarcity of allowances could not be created for Germany (as for the rest of Europe), instead there were only redistribution between the facilities of the ETS in accordance to the special rules.

The energy sector had been completely switched during the second period to a benchmark system that constitutes an emission factor for electricity of at least 365 g/kWh for combustion of gaseous fuels, otherwise 750 g/kWh. Relevant to the assigned amount were historical data again and for start-ups their assumed utilization rate. The emissions targets of the German NAP had to be exacerbated to appropriate the European Commission's decision (European Commission, 2006). To determine the allocation amount one resorted to scenarios of the model PRIMES (Capros, 2013) so that the concurrent promotion of renewable energy is (indirectly) considered. Compared with the base period, the allowable emissions were reduced by 40.1 million tonnes a year, or around 8.1 % (Federal Ministry for the Environment, 2006). However, the Clean Development Mechanism (CDM) and Joint Implementation (JI) allowed to count credits (CERs, ERUs) for climate protection projects in developing and emerging countries for emissions in the ETS. Until April 2012, the amount of credits filed in Germany; on the average, was around 40.6 million annually, or about the savings intended in that period. Overall, about 435 million CERs and ERUs are permitted in Germany until 2015 (Deutsche Emissionshandelsstelle, 2012), and because of the transferability of certificates, it is expected at the start of the third trading period a surplus of around 235 million certificates, in addition to substantial surpluses by the financial and economic crisis, which amounts to 650 million certificates all over Europe (Neuhoff and Schopp, 2013). For the whole EU the number of CERs and ERUs continue to increase the supply of allowances in the third trading period of an additional 1.68 billion certificates (Neuhoff *et al.*, 2012). Already by these two effects, the surplus exceeds the total anticipated emissions reductions for the third trading period (1.95 billion). So compared to the second trading period, up to 2020 no additional savings within the EU are required. These developments have led to sustained price erosion of certificates since the end of 2008.

2.2 Indicator for the evaluation of the ETS

In like of the functions and problems of the ETS described above, a suitable evaluation indicator should only take into account possible emission reductions that are actually attributable to the ETS, which obviously does not apply to emission reductions due to the financial and economic crisis for example. Ellerman and Buchner (2008) use an approach, which compares the emissions in the framework of the ETS with a business as usual (BAU) scenario. But that does not adjust for emission reductions caused by the development of renewable energy, which also does not attribute to the ETS. Furthermore, we are only interested in the CO_2 reductions of the producers, because the default emission cap acts directly on these, whereas the consumers are only exposed to the (partially) passed on costs. Although increasing prices result in a lower demand, which is eventually linked with less CO_2 emissions, the mitigation strategy with lowest costs is regarded as efficient as higher costs lead to less consumption and thus a decrease of utility. Hence the price effect should be separated. The CO_2 savings of renewable energy is also evaluated on the basis of production only (see Section 2.4). An indicator satisfying these requirements can be found by consideration of the possible saving strategies within the fossil sector.

A simple decrease in electricity consumption reduces the emissions, but would cause an electricity gap and thus the collapse of the entire power supply. Such a sufficiency strategy comes into question only when carried out simultaneously with imports from abroad. This could for example substitute electricity from coal in Germany by those from natural gas in the Netherlands. However, on the one hand, Germany has own natural gas power plants, on the other hand, this would require an allowance price that would make this transition attractive, which was not the case so far on an annual basis (see Fig. 1). Short-term changes of the certificate price play only a minor role for such a scenario, since coal power plants have high costs for a start-up and shut-down. Additionally, the rising of German exports connected with a nearly stable import of electricity since 2003 suggests that this strategy does not matter at all in contrast to Delarue *et al.* (2008). However, for our national analysis only the impact of the ETS emission reduction within Germany is important, as long as it is sufficient to meet demand, because it is compared to the development of renewable energy within Germany.

If an efficiency strategy is pursued, the generation of a certain amount of electricity corresponds with lower CO_2 emissions. A substitution strategy will cause the substitution of emission-intensive energy sources by those with lower emissions. This can be benefited in two ways, first, with substitutions within

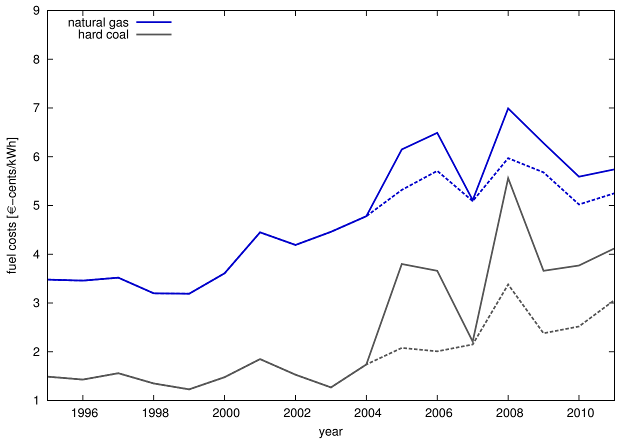

Figure 1: Evolution of fuel prices for electricity generation in Germany (incl. taxes) with CO_2 emission prices (solid) and without (dashed). Own calculations based on (Arbeitsgemeinschaft Energiebilanzen e.V, 2013; Federal Environment Agency, 2013; Statistik der Kohlenwirtschaft e.V., 2013).

the fossil sector, so that the plants continue to be subject to emissions trading, and second, in a switching to renewable energy, which means a withdrawal from the ETS. Due to the gap in MAC a substitution with renewable energy is currently not induced by the ETS (see Section 1) as described, even the substitution of emission-intensive fuels with natural gas, the ETS could hardly cause. In the first trading period, there was a provision in Germany, which allowed a power plant operator to transmit all allowances allocated to a new power plant, if the old one has been removed from operation. This would be especially viable for a switch from coal to gas, this means about half of the emission rights would no longer be used and may be sold. However, this provision has been exercised only once, so obviously it was not very lucrative. In the following trading periods this regulation was finally deleted (Deutsche Emissionshandelsstelle, 2009).

Given the described opportunities to reduce emissions, it is useful to put the annual emissions of the ETS underlying electricity industry E_i^f in ratio to the totally generated electricity S_i^f, and thus determine the emission factor of fossil fuel for electricity for each year i.

$$e_i^f = \frac{E_i^f}{S_i^f} \tag{1}$$

This evaluation indicator reflects both emission reductions through an improvement in efficiency and possible substitutions within the fossil sector and thus describes the possible and relevant mitigation strategies of producers.[2] In contrast to the consideration of absolute emissions changes, it has the advantage to be unaffected by the economic development and the increased use of renewable energy. Thus the two major special effects, affecting the absolute emissions beyond the ETS, are eliminated. The changes in emissions compared

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[2] Only savings in consumption of power plants are not included in the evaluation indicator. However, this may be neglected due to their low total percentage (<10 %).

to the base period and adjusted for these special effects are given by

$$\Delta E_i^f = \left(e_0^f - e_i^f\right) S_i^f . \tag{2}$$

This expression can be normalized by the average generated electricity by fossil fuels in the period of observation $\bar{S}^f$ and subtracted from the emission factor of the base period e_0^f yielding an emission factor, which is normalized and adjusted for special effects

$$\begin{aligned} \tilde{e}_i^f &= e_0^f - \frac{\Delta E_i^f}{\bar{S}^f} \\ &= \frac{E_i^f}{\bar{S}^f} + \left(1 - \frac{S_i^f}{\bar{S}^f}\right) e_0^f \end{aligned} \tag{3}$$

For an invariant fossil power generation ($\bar{S}^f = S_i^f$) Eq. 3 turns into Eq. 1. But Eq. 3 is necessary to establish the comparability with the evaluation indicator of renewable energy (Eq. 11), which otherwise would not be given over time due to the fluctuating annual value of S_i. However, it is likely that the CO_2 savings observed by the indicator will not be solely due to the ETS, especially since price increases of the required fossil energy sources also provide an incentive for saving both fuel and emissions (see Fig. 1). Hence, the effectiveness of the system is slightly overestimated.

2.3 Adjustment of the ETS

Up to now, the stated objectives of the ETS have been exclusively based on absolute emission reductions, setting the number of annually allowed emission certificates E_i before each trading period. Therefore unpredicted emission changes directly affect certificate demand and price. This connection results in no additional emission reductions with an increasing use of renewable energy but decreasing certificate prices (Rathmann, 2005). To get an effective combination of both policy instruments a decoupling of this mechanism is highly desirable. Other special effects such as economic development can also make phases occur without incentives by the ETS to reduce emissions due to very low prices (see Section 2.1). While the objective will still be achieved, the expected a priori measures to reduce emissions will not be exhausted. But more intensive early emission reductions create the opportunity to weaken subsequent objectives or those in other sectors with the same effect on climate, because ultimately only the cumulated emissions are relevant. This describes a cost advantage, since MAC is assumed to increase with increasing mitigation of emissions (see Eq. 12). Phases without reduction incentives are therefore causing opportunity costs, which depend on an assumed discount factor of course. However, emission targets are not axiomatic but a compromise between abatement costs and expected damage. If abatement costs turn out to be lower than expected while the expected damage remains unvaried, a higher reduction objective is the logical consequence. So, the intermediate objectives of the EU are always linked to an expected certificate price leading to a reasonable burden. Hence, a far lower price than expected causes opportunity costs. While the ETS provides tools with regard to a limitation of the certificate price (European Parliament and Council, 2009), such tools for a drop in prices are weaker. To avoid opportunity costs in the electricity sector, a flexible cap, based on an EU-wide fossil fuel emissions factor as described in Eq. 1, could be introduced. As every target in absolute emission reductions E_i implicitly considers a certain expected electricity output S_i^e a transmission to the corresponding emission factor e_i can be easily done

$$e_i = \frac{E_i}{S_i^e}. \tag{4}$$

The introduction of absolute emission levels by the Kyoto Protocol reinforces cap-and-trade emission trading schemes with absolute emission objectives (e.g. ETS) as dominant model, while relative targets were quite common in connection with other environmental policy instruments such as baseline-and-credit programs (Egenhofer, 2003). The advantage of relative targets is the decoupling of the ETS from special effects, which result in a deviation of the actual output of electricity S_i from the expected one S_i^e.

$$\Delta S_i = S_i^e - S_i, \tag{5}$$

finally resulting in a corresponding difference in emission certificates

$$\Delta E_i = \Delta S_i e_i. \tag{6}$$

The disadvantage of relative emission targets in the context of the ETS, as mentioned by Rathmann (2005), is the uncertainty to reach an absolute objective. To continue guaranteeing absolute objectives, the cap is made only flexible to lower emissions. That is why overall a change in the number of certificates will only appear during a trading period of n years, if the produced electricity has been lower than expected. Hence, the cumulative deviation is less interesting than the resulting reserve R_i, which is defined for positive values only

$$R_i = \max\left\{0, \sum_{j=1}^{i} \Delta E_j\right\}. \tag{7}$$

The idea of the flexible cap is to subtract the amount of excessive emission certificates, occurring in year i from the expected amount of certificates to be auctioned in year $i+1$. In contrast, if there is a scarcity of emission certificates, because of a high electricity production in year i, the number of missing certificates will only be added to the auction in year $i+1$, if the reserve is positive or will be positive up to year n. These considerations yield an adjusted number of certificates

$$\tilde{E}_i = E_i - \max\left\{\Delta E_{i-1}, -R_{i-2}\right\} + \min\left\{\left|\Delta E_{i-1}\right|, D_{i-1}\right\} \tag{8}$$

with

$$D_i = \sum_{j=1}^{i} \left(E_j - \tilde{E}_j - \Delta E_{j-1}\right). \tag{9}$$

D_i only has positive values, if in the past years the reserve was not sufficient to generate enough additional certificates to compensate a high electricity production. These missing certificates are only added, if in the following years there will be excessive certificates. It is important to note, that the adjustment takes place according to a predetermined and therefore, anticipatable mechanism for market participants. Compared to other suggestions (European Commission, 2012) the mechanism has the advantage to be purely quantity based. In contrast to Diekmann (2013) there is no need for a definition of special economic situations to justify an ex-post correction of the cap. Hence, our mechanism is more predictable and corrects more unforeseen situations. Production declines due to economic development, the addition of renewable energies or even a warm winter are made neutral to ETS prices, so that opportunity costs as a result of a price decline can be avoided. The fluctuations of the certificate price are expected to weaken significantly, reducing the uncertainty for emission-reducing investments accordingly. This leads to a stabilization of investment activities, so periods of low financial charges do not change with such of high charges.

On the other hand Eq. 8 ensures that a lower than expected development of renewable energies has an impact on the ETS to provide a secure compliance of the jointly formulated objective for both environmental policy instruments. Also an increase in the amount of electricity production has, as yet, an effect on the ETS. Nevertheless, in order to prevent possible overheating of the market, it makes sense to link the use of CERs and ERUs to a certain price level of allowances so that the price-dampening effect only appears for this particular case as suggested by citeEU-COM-652. This also gives legitimation to the introduced partial flexibility, which only enables lower absolute emissions. The described mechanism should be restricted to the electricity sector, because other sectors face a stronger international competition and have the opportunity to storage products.

2.4 Promotion of renewable energy

The Renewable Energies Act (EEG) forms a foundation of the promotion of renewable energy in Germany, which guarantees both the purchase of generated electricity and a minimum technology-dependent price for a certain period of time (feed-in tariff). This minimum price is usually higher than the market price but declines over time. Thus the CO_2 abatement costs arising from the analogous promotion scheme correspond in particular to the difference between the guaranteed feed-in tariff and the market value of the generated electricity. In addition, there are comparatively low costs of forecasts, stock exchange listing, extra balancing energy etc. However, the distributed generation of renewable energy relieves distribution networks, which is associated with savings. Costs arising from the promotion will be passed onto consumers of electricity, whereas energy-intensive companies are largely exempted. Since 2010, the annual forecast sought to calculate the apportionment is performed by the Ordinance of a Nationwide Equalisation Scheme (AusgleichMechV) that takes into account all costs and savings mentioned.

The inflexible pricing of the EEG has resulted, mainly in the field of photovoltaics, in an excessive promotion in Germany, causing undesirable distributional effects. The price reductions achieved through technological advances exceeded the statutory reductions by far for a period of time. As a result, a solar boom was triggered, changing the electricity mix and its cost structure sustainably.

At the moment the integration of renewable energy into energy markets causes problems, because the pricing on the electricity market is based exclusively on variable costs. Subsequently, causing all available power plants to meet demands at any given time are ordered according to their variable costs (merit order). The last essential, and hence most expensive power plant, determines the price. Apart from this price-setting power plant all the others can generate a contribution to cover their costs of capital. In this way, a mix of base, medium and peak load plants developed, where base load power plants have high costs of capital and low variable costs, while the reverse is true for peak load power plants. The differentiated cost structure of power plant types is caused by the different duration of their use.

Since, in particular, photovoltaic and wind power have virtually no variable costs, their usages change the merit order. In the short and medium term, the supply curve shifts to higher capacities and the current market price decreases (Sensfuß *et al.*, 2008). Consequently, fossil fuel power plants are used less and there is an excess capacity. In the long-term, power plants can adapt and the described merit order effect of renewable energy disappears, if a fossil base load remains necessary for meeting the demand (Weber and Woll, 2007). With an increasing ability of renewable energy to provide base load power, as it sometimes does even now in the case of Germany, in particular base load power plants will be squeezed out of the market in the long run, as their shorter use makes it no longer possible to cover the costs of capital (Fürsch *et al.*, 2012). In the short and medium term, however, the reverse is true, because of the irrelevance of capital costs. The use of the existing fleet of power plants with excess capacity (sunk costs) results in a crowding out of medium and peak load power plants because of their higher variable costs, making the current market mechanism the composition of the power plants' fleet drift away from the long-term equilibrium. The anticipation of this development can hardly counteract as, specifically, base load power plants operate for several decades. Investment in gas-fired power plants will hardly take place under these conditions, although their flexibility will be of major importance for future electricity supply due to increasing fluctuations caused by renewables.

Caused by the merit order effect of renewable energy, the decline of electricity market prices in connection with feed-in tariffs automatically leads to a significant increase in the differential costs building up the EEG apportionment, leading to systematically overestimated costs. Additionally, there is redistribution from consumers in the payment of apportionment to companies, who are largely exempted from the apportionment and also benefit from lower market prices.

2.5 Indicator for the evaluation of renewable energy

The success of renewable energy, in terms of emission reductions, can only be evaluated relative to fossil energy by determining how high the emissions would have been (by fossil fuels) for an equivalent amount of electricity generation. Because of the discussed merit order effect, renewable energy will at first replace gas and oil power plants, which have relatively little CO_2 emissions. However, in the long run there will be at least a substitution of power plants with average emissions and with the beginning provision of base load electricity emissions-intensive base load power plants will be disproportionately substituted. This long-term development is induced by the current installation of renewable generation capacity. Hence, the promotion of renewable energy in the long run will result in shifts from coal to gas-fired power plants, in addition to the ETS. This justifies at least taking current average emissions of fossil based power plants as a basis for emission savings via renewable energy. The occurrence of short and medium term merit order effect is neglected in terms of costs and in that of emissions. In addition, only direct emissions are taken into account, since these are the basis for the ETS. According to (Memmler *et al.*, 2009, p. 49) only 93 % of emissions are credited by non-regulated renewables (wind, solar), due to the additional expenses incurred by requiring extra balancing energy. Analogous to Eq. 2 this yields

$$\Delta E_i^r = e_i^f S_i^r p \tag{10}$$

with $p = 0.93$ for non-regulated renewables and $p = 1$ in any other case. To make a comparison with the evaluation indicator of the ETS possible, it makes sense to compare the CO_2-savings with the base period of the ETS and express them relative to the average electricity produced by fossil fuels in g/kWh.

$$\tilde{e}_i^r = e_0^f - \frac{e_i^f S_i^r}{\bar{S}^f} p \tag{11}$$

3 The model

The electricity generation of an economy in the BAU scenario results in a specific emissions level $e^{''}$. Assuming a total abatement of emissions in the long run within the electricity sector, because of mitigation strategies in other sectors being even more intricate, we are very close to the long-term emission objectives of both EU and Germany. With the introduction of the ETS, an emission target $e^{'}$ is formulated, which limits the number of necessary allowances. According to standard environmental economic theory, e.g. Nordhaus (1991), the price of the emission certificates corresponds to the MAC and increases with an exacerbation of the emissions cap

$$\frac{\mathrm{d}MAC(e^{'})}{\mathrm{d}e^{'}} = \frac{\mathrm{d}p(e^{'})}{\mathrm{d}e^{'}} < 0. \tag{12}$$

The integral of the price from 0 to the emissions cap defines the total remaining emission costs, which are assigned as external costs without emissions trading

$$\int_0^{e^{'}} p(e)\mathrm{d}e = C^{ext}(e^{'}). \tag{13}$$

On the other hand the product of price and allowed emissions contributes to the part of the external emission costs, which is already internalized due to the selected emission target

$$C^{int}(e^{'}) = p(e^{'})e^{'}. \tag{14}$$

During the initial phase of emissions trading, only a small part of the external costs is internalized. When auctioning $C^{int}(e^{'})$ corresponds to the revenue for the provision of the atmosphere as public good. But as free allocation is mainly carried out in the first two phases and companies nevertheless pass these costs onto consumers, they obtain windfall profits. A difference arises only from the distribution. Identification of the abatement costs $C^{ab}(e^{'})$ to achieve the emission target $e^{'}$ can be difficult in reality, as there is a superposition of different effects (see Section 2.1).

In contrast to the ETS, the marginal abatement costs of renewable energy MAC$_r$ only depend on a small amount of its CO$_2$-savings and the resulting emission level $e^{'}$. Although the increased production of renewable energy causes additional costs due to the weather dependency, economies of scale and learning effects can be realized. Also reaching the long-term reduction target without the partial substitution by renewable energy is impossible (see Section 1). Therefore

$$\frac{\mathrm{d}MAC_r(e^{'})}{\mathrm{d}e^{'}} > \frac{\mathrm{d}MAC_{ets}(e^{'})}{\mathrm{d}e^{'}} \tag{15}$$

is a logical assumption. Abatement costs $C_r^{ab}(e^{'})$ to achieve the emission level $e^{'}$ arising from the use of renewable energy equal approximately the differential costs, since other costs and expenses, at least so far, largely cancel out each other and have little impact (see Section 2.4)

$$C_r^{ab}(e^{'}) \approx C^{dif}(e^{'}). \tag{16}$$

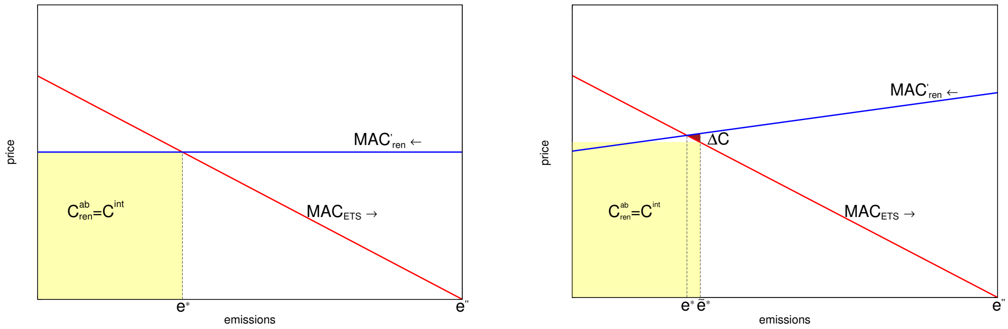
To estimate the emission level of the MAC parity, we assume at first linear MAC with MAC$_r$ to be constant. This represents a balance between the costs for the integration of renewable energy and the savings through learning effects. Empirical data show that this assumption is plausible (see Fig. 5). In this case, the appropriate emission level e^* of the MAC parity is reached if

$$C^{dif}(e^*) = C^{int}(e^*) \tag{17}$$

holds. Moreover, for all $e^{'} \geq e^*$ we get

$$C^{dif}(e^{'}) \leq C^{int}(e^{'}). \tag{18}$$

To illustrate this relationship graphically, it makes sense to change the direction of the abscissa for MAC$_r$, so that the emissions for MAC$_r$ increase to the left and for MAC$_{ets}$, as usual, to the right (see Fig. 2). $C_r^{ab}(e^{'})$ is lower than $C^{int}(e^{'})$ until MAC parity is reached. Thus, under the above assumptions the optimal long-run share of mitigated emissions by renewable energy is not yet reached, if Eq. 18 is met. Then furthering the promotion of renewable energy simultaneously to the ETS does not violate the minimum cost path. This presumes no difference in efficiency between the set up of renewable energy capacity by subsidies on the one hand and the ETS on the other hand. The result is an identical MAC$_r$ curve in Fig. 2 for both methods. This comes true for promotion of renewable energy by a quota system, because it introduces the cheapest renewable technology like the ETS would do in its resulting sequence of mitigation strategies. Possible additional costs according to one of the two methods have no welfare effect. But feed-in tariffs have stronger incentives and, despite the rigid price setting, less technology-specific electricity production costs due to lower investment risks. Hence, they are largely enforced over quota systems in the EU (European Commission, 2011). This does not contradict our model, because it does not give advice for an efficient promotion of renewable energy but focuses on the possibility of an efficient combination of both policy instruments. Inefficiencies with respect to one of the policy instruments do not concern their combination but solely the framework of each instrument.



(a) Behavior for $m_r = 0$

(b) Behavior for $m_r > 0$

Figure 2: Schematic depiction of MAC. Emissions increase for MAC$_{ets}$ to the right, for MAC$_r$ to the left.

Without the assumption MAC$_r = const.$ Eq. 17 only holds approximately, so the emission level $\tilde{e}^*$, which can be calculated by Eq. 17 is deviating from the one of MAC parity e^*. For increasing MAC$_r$ the MAC parity is met before fulfillment of Eq. 17, for decreasing MAC$_r$ thereafter. In the case of increasing MAC$_r$ the promotion of renewable energy up to the fulfillment of Eq. 17 increases the total abatement costs C, because the share of emissions, which are mitigated with renewable energy is too big and hence not optimal (see Fig. 2 b). For the evaluation of the described method to calculate the emission level of the MAC parity, finally leading to the optimal shares of renewable energy and other mitigation strategies, it is useful to do a worst case scenario estimation for the ratio of additional costs and total abatement costs ΔC^{rel} caused by increasing MAC$_r$. For this approach linear MAC of any type are assumed (e.g. Fig. 2b).

$$MAC_r(e^{'}) = -m_r e^{'} + b_r^{'} \tag{19}$$

$$MAC_{ets}(e^{'}) = m_{ets} e^{'} + b_{ets}, \tag{20}$$

with

$$b_r^{'} = b_r + m_r e^{''}. \tag{21}$$

The relative additional costs ΔC^{rel} can be determined analytically (see appendix A)

$$\Delta C_{rel.} = \frac{-m_r^2 m_{ets}(b_r^{'} - b_{ets})^2}{4(m_r + m_{ets})(m_{ets}^2 b_r^{'2} - \frac{1}{4} m_r^2 b_{ets}^2 - m_r m_{ets} b_{ets}^2 - 2m_{ets} b_r^{'})}. \tag{22}$$

It turns out that ΔC^{rel} reaches the maximum when on the one hand $b_{ets} \gg b_r$ holds, which is plausible with respect to the limited potential of emission savings of the ETS. But the crucial point is the ratio of the MACs' slopes. For $m_r/m_{ets} = 2$ the relative additional costs reach a maximum share of $\frac{1}{9}$ of the total abatement costs. However, this slope ratio contradicts the condition of Eq. 15. Under its consideration, a share of 10 % at its maximum arises in the limits of identical slopes. At lower slope ratios, the relative additional costs decrease accordingly (see Fig. 3).

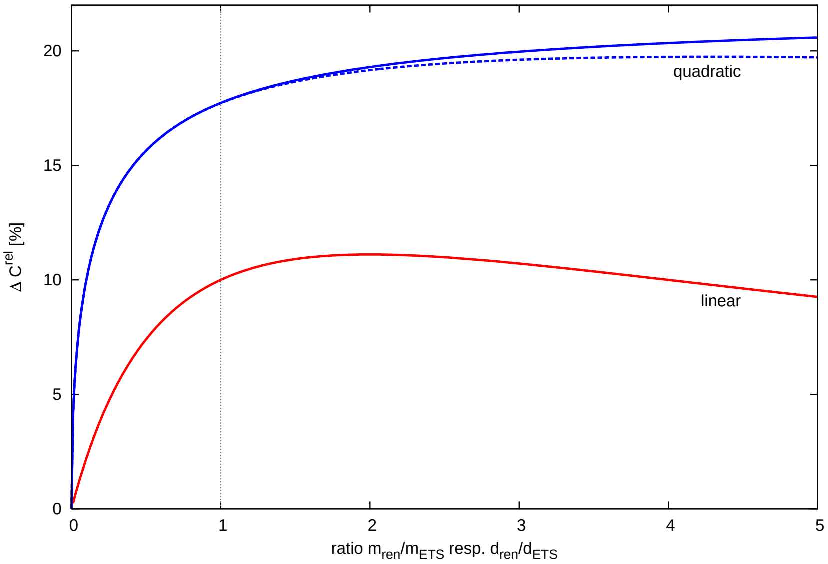


Figure 3: Evolution of the relative additional costs ΔC^{rel} with linearly (red) and quadratically (blue) rising MAC. The blue dashed curve is for $m_{ets} = 0$, while the solid is the result of m_{ets} to be chosen maximizing ΔC^{rel}. According to Eq. 15 only the part left to the dashed vertical line is of concern.

Assuming a quadratically increasing MAC, the maximum relative additional costs ΔC^{rel} can be determined by a general approach, too

$$MAC_r(e^{'}) = -m_r e^{'} + b_r^{'} + d_r e^{'2} \tag{23}$$

$$MAC_{ets}(e^{'}) = -m_{ets} e^{'} + b_{ets} + d_{ets}(e^{''} - e^{'})^2 \tag{24}$$

with

$$b_{ets} = -m_{ets} e^{''}. \tag{25}$$

In contrast to the linear behavior of the MAC no analytical calculation of ΔC^{rel} is possible. Numerical calculations show that the global maximum is reached at a level of 21.7 % of the total abatement costs, if

$$b_r^{'} = m_r = d_{ets} = 0. \tag{26}$$

These values of parameters describe linearly increasing MAC_{ets} and quadratically increasing MAC_r, what is extremely implausible (see Eq. 15), but useful as a reference case. Calculations for purely quadratic MAC ($b^{'}_r = b_{ets} = m_r = m_{ets} = 0$) show that only the ratio d_r/d_{ets} is crucial, and not their absolute values. This is also true for $m_{ets} \neq 0$ where the ratio m_{ets}/d_{ets} is relevant. The influence of the linear term rises nearly proportionally for increasing values of d_r/d_{ets} (see Fig. 7). In the limit of an infinitely large ratio, the transition to the reference case finally occurs. But in consideration of Eq. 15 the ratio is limited to 1 as for identical values of d. For that case, the relative additional costs have a share of up to 17.7 % (see Fig. 3). More details on the calculations can be found in Appendix A. The results turn out to be exactly the opposite for decreasing MAC_r of course leading to an early stop of the promotion of renewable energy.

3.1 Empirical application

The empirical application of the model (see Section 3) enables us to judge whether at a certain level of CO_2 mitigation a further promotion is following the path of minimal costs. In this case Eq. 18 will hold in the limits of our findings of the worst case estimation. Hence, we need to identify C^{dif}, C^{int} and their corresponding emission levels to calculate their normalized and adjusted emission factors as drived in Section 2. According to Eq. 3, 11, 14 and 16 we need the following data:

S_i,S_i^f,S_i^r: annual electricity production of fossil, renewable and total energy additionally allowing the calculation of the averaged values $\bar{S}$, $\bar{S}^f$
E_i^f: annual emissions of fossil fuel use allowing the calculation of e_0^f
$p(e_i^f)$: annual average price for emission allowances
$C^{dif}(e_i^r)$: differential costs arising from the difference between feed-in tariffs for renewables and the power exchange market price

Although the countries that are participating in the ETS are obligated to an annual reporting of the verified emissions table (VET reports), these reports do not have to include the amount of electricity generated within the ETS underlying electricity sector. In addition, the classification in various companies' activities are not made clear-cut. Especially for the converting processes of industrial plants, there are again and again interchanges between the industrial and energy sectors. The monitoring in the context of ETS is therefore unreliable with regard to the assessment of the evaluation indicator.

Germany's annually published energy balances reveal both the current amount of electricity generated S_i, S_i^f and the resulting primary energy consumption by energy sources (Arbeitsgemeinschaft Energiebilanzen e.V, 2013). Together with the lignite statistics (Statistik der Kohlenwirtschaft e.V., 2013) and the energy source-specific emission factors, which are published in the National Inventory Report (Federal Environment Agency, 2013) this allows CO_2 emissions of electricity generation in the fossil sector E_i^f to be determined. It can also be assumed that almost all fossil power plants are subject to emissions trading. This assumption is supported by a comparison of the calculated emissions from electricity and district heating as described above with the data reported in the VET reports, since the variations run largely analogously (see Table 1). The absolute numbers are not essential anyway, since the analysis requires only values relative to the base period.

The certificate price $p(e_i^f)$ is determined on an annual average. In 2005, due to lack of other data, up to the middle of September forward prices were used, followed by the price quotations of the spot market (Deutsche Emissionshandelsstelle, 2009, p. 95). As of 2006, the average price of the December Futures of the European Climate Exchange (2013) was evaluated for determination of $p(e_i^f)$.

The amount of electricity generated by renewable energy in promotion by the EEG S_i^r can be found in the annual accounts of transmission system operators (TSO), which have been published since 2000 (EEG/KWK-G, 2013) and even distinguish the data according to the various renewable energy technologies. These accounts also include the payments for renewable energy according to the promotion mechanism, so that together with the relevant power exchange market prices (European Energy Exchange, 2013) C^{dif} can be calculated. This calculation corresponds to the specifications applicable for the calculation of the EEG apportionment according to AusgleichMechV. However, it is in the EEG to forecast a levy, while we perform an ex-post analysis.

To improve the visual evidence of the identified costs, it makes sense to assess them in relation to average total electricity produced during the period of consideration $\bar{S}$. This yields the costs contribution of consumers per produced amount of electricity on average, which are caused by the implementation of the ETS and the promotion of renewable energy[3] (see Fig. 4).

4 Results

The data analysis of the ETS provides a quite diffused picture that apparently does not follow any rule or even seems to bring the assumed shape of MAC_{ets} given in Eq. 12 into question. This impression is capable, considering the effect-relationship described in Section 2.1 and the corresponding classification of data points into groups. After the publication of the first emission data by EU Member States at the end of April 2006, it was already clear that the first trading period would be marked by a massive over-allocation, leaving only trading before April 2006 unaffected. The second trading period was characterized by the penetration of the financial and economic crisis on the real economy from the end of 2008, what again resulted in a massive oversupply. This has held due to the transferability of the certificates up until today. Most likely, the years 2005, 2006 and 2008 are grouped together because only they can be regarded as relatively free of special effects. The remaining years are

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[3] This applies to the case that both the costs of the ETS are fully passed on to electricity consumers, for which there are some evidence (Sijm *et al.*, 2006) and the costs of renewable energy are spread to gross electricity generation and not just to a part of net electricity generation.

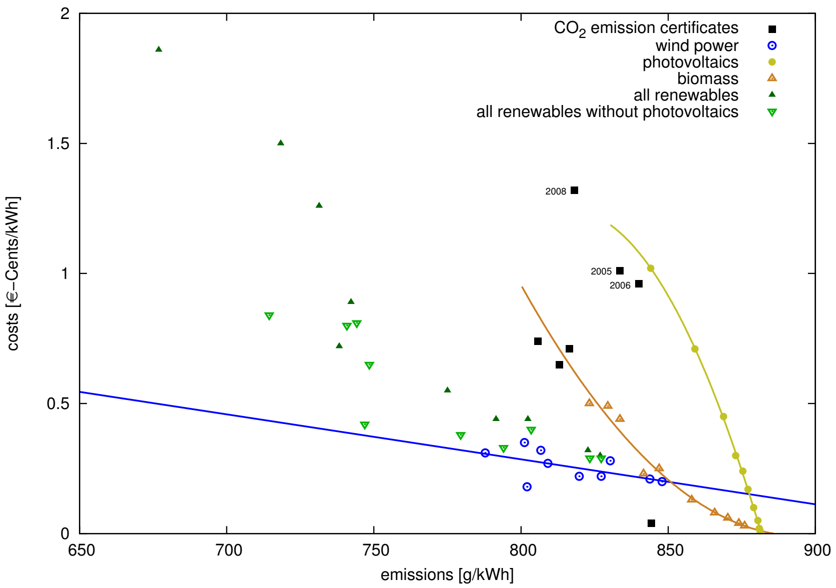

Figure 4: Already internalized external costs of ETS C^{int} and abatement costs of renewable energy C_r^{ab} in 2010 prices. Own calculations based on Federal Environment Agency (2013); Arbeitsgemeinschaft Energiebilanzen e.V (2013); Statistik der Kohlenwirtschaft e.V. (2013); EEG/KWK-G (2013)

strongly influenced by special effects; this is especially the case for year 2007. Due to oversupply and the inability to transfer the certificates to the next trading period, there was a corresponding collapse in the market, making the certificates almost worthless. Taking into account this grouping, there seems to be evidence to the plausible course of MAC according to Eq. 12 (see Fig. 4). However the very few data points make a definitive statement concerning the course of C^{int} respectively MAC$_{ets}$ impossible, although a course according to Eq. 12 is likely.

In connection with the emission certificate price, we must take note that in reality it does not exactly correspond to MAC$_{ets}$ because it is also influenced by future expectations of the market's participants. The greatest reductions among the electricity sector took place in 2003 and 2008, although the ETS started in 2005 (see Table 1). However, the expectations with respect to the ETS may have induced first emission reductions during the according consultations, which lead to the agreement of the ETS in October 2003. But because of an oversupply in the first trading period, the additional measures were no longer pursued. Only at the beginning of the second trading period, which was not directly influenced by the financial and economic crisis, such mitigation efforts were strengthened again. Now the EU targets for 2020 can be fully achieved by CERs and ERUs (see Section 2.1). As a result it can be assumed that the certificate price is currently closer to the world's MAC$_{ets}$ than to European MAC$_{ets}$ and, that the price is considerably lower due to the lower level of technology compared to Europe.

Renewable energy shows a clear correlation between increased emissions and rising abatement costs with a comparatively small increase of costs up to an emission level of about 775 g/kWh followed by a strong one to lower emission levels (see Fig. 4). This behavior can be explained by decomposition into the various renewable energy sources. Around this emission level, which was reached in 2006, a massive expansion of photovoltaics began (see solar boom, Section 2.4) while the renewable energy generation promoted by the EEG before was mostly based on wind power. Because photovoltaics were significantly more expensive compared with wind power, it resulted in an increase in the cost of renewable energy in entirety. In this context, it is important to mention that the costs listed here include the producer surplus. While this is also true for the ETS, this has an increased relevance in the field of renewable energy, since due to the structure of the EEG, very high producer surpluses were sometimes generated.

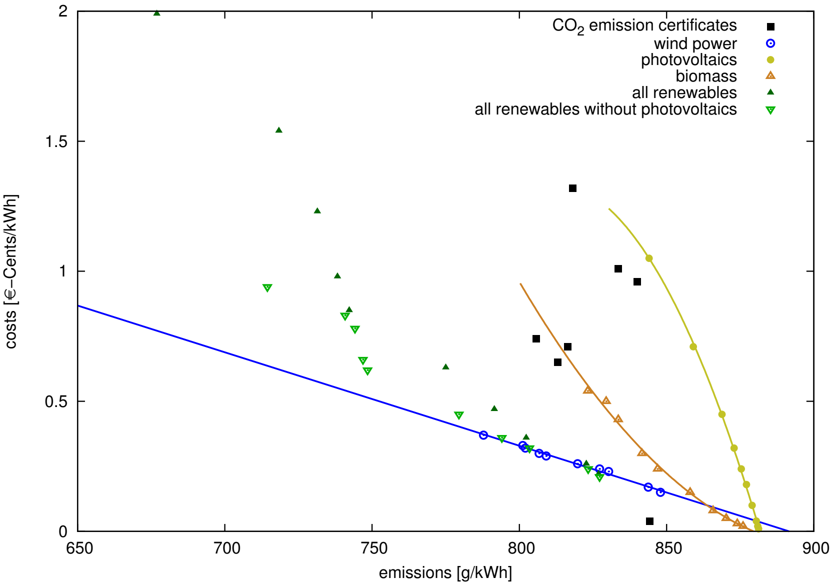

Figure 5: Already internalized external costs of ETS C^{int} and abatement costs of renewable energy C_r^{ab} in 2010 prices under the assumption of a constant average exchange price for electricity. Own calculations based on Federal Environment Agency (2013); Arbeitsgemeinschaft Energiebilanzen e.V (2013); Statistik der Kohlenwirtschaft e.V. (2013); EEG/KWK-G (2013)

The cost of the main components of renewable energy (wind, solar and biomass) can be described very well by linear or quadratic functions (see Fig. 4). It is worth noting that, in particular fluctuations in the power exchange market prices have a significant impact on the differential costs C^{dif} shown. The assumption of a constant average exchange price for electricity eliminates this effect and improves the description of the data by the appropriate functions (see Fig. 5). Regarding the MAC the evaluated data can be described by a linear course, which is decreasing for photovoltaics, constant for wind power and increasing for biomass. Hence the case of quadratic MAC$_r$ as discussed in Section 3 is practically irrelevant so far and the maximum additional costs due to a simultaneous promotion of renewable energy in the presence of the ETS are restricted to 10 % of the total abatement costs. A more accurate estimate is impossible at the moment due to lack of prospective data of the ETS without being affected by special effects (see Fig. 3). Although the functions describe the present data with high accuracy, their further course is not realistic because, for example photovoltaics at a certain level of emissions would turn into negative costs. Thereto the poor knowledge of future progress of MAC is clear and would result in high errors, if the efficient share of renewable energy is determined by the intersection point of MACs, which underlies a very rough assumption. This shows the advantage of our method as the maximum deviation can be narrowed down and quantified. Overall, it can be seen that the internalized costs of the ETS C^{int} for a particular level of emissions are above the appropriate differential costs for renewable energy C^{dif}. Considering that the only exception occurring within the data of the ETS is from 2007, which is unusable (see above), the present data show that Eq. 18 has always been fulfilled.

Assuming a long-term target of the almost complete mitigation of CO_2 emissions in the electricity sector, this means that the promotion of renewable energy up to an emission level of about 800 g/kWh was still on the path of minimum costs. Since only emission reductions were preferred, it would have been carried out also in the future as its sole use of the ETS. This emission level was reached in 2004. For the following emission levels, no statements can be made because of missing data due to the affection of the ETS by special effects as described above. Moreover, the efficiency of the use of renewable energy in addition to ETS does not mean that the support scheme itself could not be more efficient to avoid undesirable distributional effects in the form of a significant producer surplus. In connection with Fig. 4 it should be noted that the success in mitigation of emissions shown for the ETS as well as the cost of renewable energy are somewhat overestimated (see Section 2.1, 2.4).

In the years 2005 to 2011 the mitigation of CO_2 emissions within the German electricity generation amounted to about 155.3 million tons of CO_2 by ETS and about 387.7 million tons of CO_2 by renewable energy (see Table 1). However, since the promotion of renewable energy in Germany started in 1996, an advantage with time is expected. But Figure 4 also shows, that more emissions are mitigated by renewables than by the ETS, if the same price effect with respect to gross electricity generation is considered.

5 Conclusion and outlook

The theoretical considerations introduced in this paper allow an estimation of whether the promotion of renewable energy in combination with the ETS follows a cost minimizing path. Under consideration of current data we find out, if the share of electricity generation with renewable energy already exceeds the efficient share, which is necessary to achieve long-term emission targets. An excess of the efficient share indicates a necessary modification or even a stop of the promotion of renewable energy, if only mitigation issues are considered. The model produces reliable results as any plausible variation of assumed future MAC leads to a maximum deviation of 10 % of total abatement costs for liner and of about 17 % for quadratic MAC. With regard to German empirical data it turns out, that up to now the MAC of the different renewable energy sources show a linear shape limiting the maximum deviation to 10 %. This estimation may be improved, if more data with respect to the ETS will be available in the future. According to available data in Germany the promotion of renewable energy has not caused a lost of the cost minimizing path. Hence, the existence of both policy instruments is efficient. That does not imply separate efficiency of each policy instrument due to a necessary separate analysis. But our method can evaluate individually for each country participating in the ETS if further promotion of renewable energy is economically viable. Since renewable energy is promoted on a national level this is a useful tool to review the efficiency of this policy in combination with the ETS.

In order to provide an adequate application of the model the two policy instruments are evaluated with regard to their success in CO_2 mitigation. We develop a suitable evaluation indicator which is not influenced by special effects such as the economic development or the promotion of renewable energy. Therefore emission reductions can be calculated which are adjusted for these effects. On that basis we introduce a flexible cap for the ETS in combination with a price-dampening mechanism linked to a certain price limit. This ensures the achievement of the emission objectives with certainty whilst extremely low certificate prices which do not set any incentives for emission reduction are avoided. The result is a decoupling of the development of renewable energy and the certificate price to allow a better combination of the two policy instruments. Other special effects are limited as well leading to a higher investment certainty with respect to emission reductions.

We can give two recommendations. Firstly the suggested reformation of the ETS should be realized due to low incentives in investments in emission reductions. Secondly a monitoring of the development of renewable energy according to our model is a useful tool to recognize the necessity of modifications in the promotion of renewable energy. Eventually the evaluation indicator and the empirical assessment seek for further refinement. Hence a detailed analysis of side effects (e.g. fuel costs), which are also affecting emission reductions is necessary.

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A Estimation of relative additional costs

The EU's long-term objective to prevent CO_2 provides an extensive mitigation (80-95 %). In the electricity sector that will result in saving almost the entire emissions because emission reductions in other sectors – in particular the mobility sector – are even more difficult to achieve. Crucial for the costs associated with the mitigation is the course of the marginal abatement costs of renewable energy (MAC_r) and other technologies (MAC_{ets}).

A.1 Linear MAC

Linear MACs generally yield

$$MAC_r = m_r e + b_r \tag{27}$$

$$MAC_{ets} = m_{ets} e + b_{ets} \tag{28}$$

After rearrangement of equation 28 under consideration of Fig. 2 we get

$$MAC_r^{'} = -m_r e + b_r^{'}, \tag{29}$$

with

$$b_r^{'} = b_r + m_r e^{''} \tag{30}$$

The emission level of the turning point e^* equals the intersection point of curves (reference case)

$$e^* = \frac{b_r^{'} - b_{ets}}{m_r + m_{ets}}. \tag{31}$$

Because of necessity of renewable energies to achieve the long-term objective we get

$$b_r^{'} < b_{ets}. \tag{32}$$

Additionally an adequate description of the problems requires

$$b_r^{'} > 0, b_{ets} > 0. \tag{33}$$

Back to reality the equations of MAC are not known. However, equalizing the already internalized costs C^{int} and the abatement costs of renewable energy C_r^{ab} the according emission level $\tilde{e}^*$ is obtained

$$\tilde{e}^* = \frac{b_r^{'} - b_{ets}}{\frac{1}{2}m_r + m_{ets}}. \tag{34}$$

$m_r = 0$ yields $e^* = \tilde{e}^*$, while increasing MAC_r yields $e^* \neq \tilde{e}^*$, so that the assumption $\tilde{e}^*$ as turning point causes additional costs ΔC compared to the reference case. For linear MAC_r ΔC can be calculated

$$\Delta C = \frac{-m_r^2 (b_r^{'} - b_{ets})^2}{8\left(\frac{1}{2}m_r + m_{ets}\right)^2 (m_r + m_{ets})}. \tag{35}$$

The marginal abatement costs of renewable energy C_r^{ab} can be calculated, too

$$C_r^{ab} = \frac{\left(\frac{1}{2}m_r b_{ets} + m_{ets} b_r^{'}\right)\left(b_r^{'} - b_{ets}\right)}{\left(\frac{1}{2}m_r + m_{ets}\right)^2}. \tag{36}$$

The total abatement costs C are

$$C = C_r^{ab} + C_{ets}^{ab} = \frac{1 + \frac{e^{''}}{\tilde{e}^*}}{2} C_r^{ab}, \tag{37}$$

what results in

$$C = \frac{m_{ets}^2 b_r^{'2} - \frac{1}{4}m_r^2 b_{ets}^2 - m_r m_{ets} b_{ets}^2 - 2m_{ets} b_r^{'}}{2m_{ets}\left(\frac{1}{2}m_r + m_{ets}\right)^2}. \tag{38}$$

This includes the additional costs ΔC as $\tilde{e}^*$ instead of e^* is taken into account. Finally the calculation of relative additional costs $\Delta C^{rel} = \frac{\Delta C}{C}$ is possible

$$\Delta C^{rel} = \frac{-m_r^2 m_{ets}(b_r^{'} - b_{ets})^2}{4(m_r + m_{ets})(m_{ets}^2 b_r^{'2} - \frac{1}{4}m_r^2 b_{ets}^2 - m_r m_{ets} b_{ets}^2 - 2m_{ets} b_r^{'})}. \tag{39}$$

$m_r = 0$ expectably cancels ΔC^{rel}. The estimation of maximum relative additional costs ΔC^{rel} requires a maximization with respect to m_r at first

$$\begin{aligned} \frac{\partial \Delta C^{rel}}{\partial m_r} &= \left(\tfrac{1}{2}m_r + m_{ets}\right) \\ &\quad \left(\tfrac{1}{2}b_{ets}^2 m_r^2 - m_{ets} b_{ets}^2 m_r + 2m_{ets}^2 b_r^{'2} - 4m_{ets}^2 b_r^{'} b_{ets}\right) \\ &= 0 \end{aligned} \tag{40}$$

This obtains three possible extrema for ΔC^{rel}:

$$m_r = -2m_{ets} \vee m_r = m_{ets} \pm \sqrt{m_{ets}^2 - \frac{4m_{ets}^2 b_r^{'}}{b_{ets}^2}(b_r^{'} - b_{ets})} \tag{41}$$

For a maximum $m_r m_{ets} > 0$ and according to increasing MAC additionally $m < 0$ is required, so that

$$m_r = m_{ets} + \sqrt{m_{ets}^2 - 4m_{ets}^2 \cdot \frac{b_r^{'}}{b_{ets}} \cdot \frac{b_r^{'} - b_{ets}}{b_{ets}}} \tag{42}$$

is left as only maximum, because consideration of Eq. Gl. 32 and 33 yields

$$\frac{4m_{ets}^2 b_r^{'}}{b_{ets}^2}(b_r^{'} - b_{ets}) < 0. \tag{43}$$

With respect to $b_r^{'}$ and b_{ets} the maximum of Eq. 39 can be determined by the according limiting values:

$$\lim_{\frac{b_r^{'}}{b_{ets}} \to 0} m_r = 2m_{ets}, \tag{44}$$

what leads to

$$\lim_{\frac{b'_r}{b_{ets}}\to 0} \Delta C^{rel} = \frac{1}{9} \tag{45}$$

Additionally only

$$\lim_{b'_r \to b_{ets}} m_r = 2m_{ets} \tag{46}$$

and

$$\lim_{b'_r \to b_{ets}} \Delta C^{rel} = 0 \tag{47}$$

are interesting, because of Eq. (32)

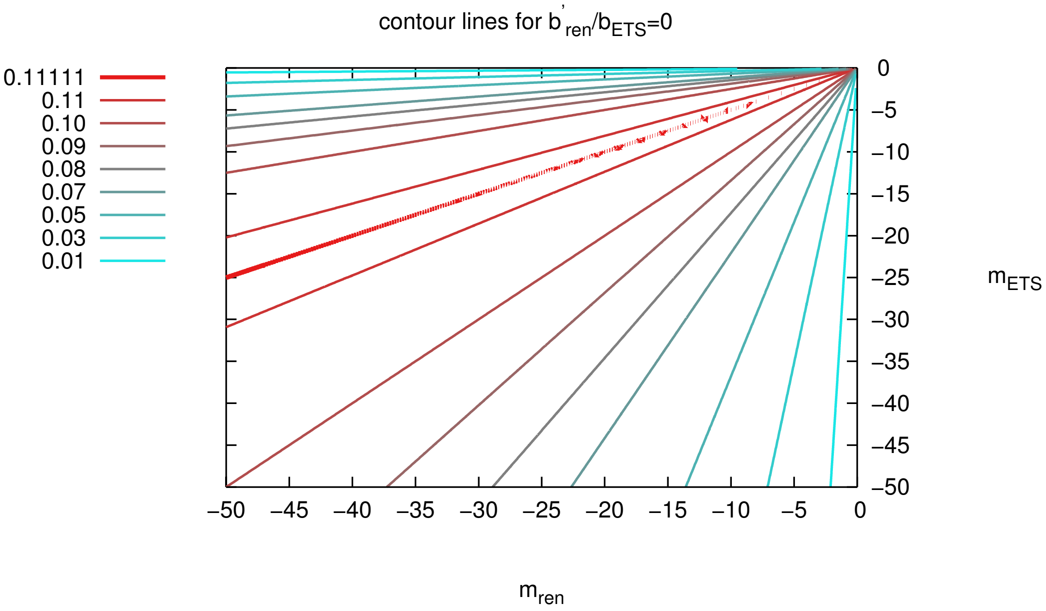

Figure 6: Contour lines of maximum relative additional costs ΔC^{rel} for linear MAC.

The maximum of relative additional costs ΔC^{rel} is obtained by a difference of axis intercepts, which is as large as possible and leads to $m_r = 2m_{ets}$. Under this condition the maximum relative additional costs reach a share of 11.1 % on total costs C.

A.2 Quadratic MAC

For quadratic MAC Eq. 28, 28 can be extended

$$MAC'_r = -m_r e + b'_r + d_r e^2 \tag{48}$$

$$MAC_{ets} = m_{ets} e + b_{ets} + d_{ets}(e' - e)^2 \tag{49}$$

with

$$b_{ets} = -m_{ets} e'. \tag{50}$$

The requested emission level e^* can be determined by the intersection point of the two curves (reference case)

$$\begin{aligned} e^* \; &= \; \tfrac{2d_{ets}e^{'}-m_r-m_{ets}}{2(d_{ets}-d_r)} \\ &\pm \; \sqrt{\left(\tfrac{2d_{ets}e^{'}-m_r-m_{ets}}{2(d_{ets}-d_r)}\right)^2-\tfrac{b_{ets}-b_r^{'}+d_{ets}e^{'2}}{d_{ets}-d_r}}. \end{aligned} \tag{51}$$

For $d_r = d_{ets}$ Eq. 51 cannot be solved, because the denominator equals 0. But consideration of this case yields

$$e^* = \frac{b_r^{'} - b_{ets} - d_{ets}e^{'2}}{m_r + m_{ets} - 2d_{ets}e^{'}} \tag{52}$$

instead of Eq. 51. Analog to Eq. 34 determination of $\tilde{e}^*$ is possible by equalization of the already internalized costs of emission $C^{int.}$ and the abatement costs of renewable energy $C^{ab}_{ren.}$

$$\begin{aligned} \tilde{e}^* \; &= \; \tfrac{2d_{ets}e^{'}-\frac{1}{2}m_r-m_{ets}}{2(d_{ets}-\frac{1}{3}d_r)} \\ &\pm \; \sqrt{\left(\tfrac{2d_{ets}e^{'}-\frac{1}{2}m_r-m_{ets}}{2(d_{ets}-\frac{1}{3}d_r)}\right)^2-\tfrac{b_{ets}-b_r^{'}+d_{ets}e^{'2}}{d_{ets}-\frac{1}{3}d_r}}. \end{aligned} \tag{53}$$

For $d_r = 3d_{ets}$ Eq. 53 cannot be solved, because the denominator equals 0. But consideration of this case yields

$$\tilde{e}^* = \frac{b_r^{'} - b_{ets} - d_{ets}e^{'2}}{\frac{1}{2}m_r + m_{ets} - 2d_{ets}e^{'}}. \tag{54}$$

instead of Eq. 53. For the additional costs ΔC, which result from the difference of $\tilde{e}^*$ and e^*

$$\Delta C = \int_{e^*}^{\tilde{e}^*} \left((d_r - d_{ets})e^2 + (2d_{ets}e^{'} - m_r - m_{ets})e + b_r^{'} - b_{ets} - d_{ets}e^{'2}\right) \mathrm{d}e \tag{55}$$

is obtained. The abatement costs of renewable energy

$$C^{ab}_r = \int_0^{\tilde{e}^*} \left(d_r e^2 - m_r e + b_r^{'}\right) \mathrm{d}e \tag{56}$$

and the abatement costs of the ETS C^{ab}_{ets} can also be calculated

$$C^{ab}_{ets} = \int_{\tilde{e}^*}^{e^{'}} \left(d_{ets}(e^{'} - e)^2 + m_{ets}e + b_{ets}\right) \mathrm{d}e. \tag{57}$$

Hence total abatement costs C are

$$C = C^{ab}_r + C^{ab}_{ets} \tag{58}$$

finally leading to the requested relative additional costs

$$\Delta C^{rel} = \frac{\Delta C}{C}. \tag{59}$$

Numerical calculations show, that the global maximum is reached for $b_r' = m_r = d_{ets} = 0$ what, however, contradicts the plausible assumption of comparatively more increasing MAC$_{ets}$ (see Eq. 15). Under consideration of this condition only $0 \leq \frac{d_r}{d_{ets}} \leq 1$ turns out to be relevant, what leads to a maximum of ΔC^{rel} for $b_r' = m_r = 0$ and increases with decreasing values for d_{ets}, because

$$\lim_{d_{ets} \to 0} \frac{d_r}{d_{ets}} = \infty, \tag{60}$$

what is equivalent to a transition of parameter properties to the global maximum.

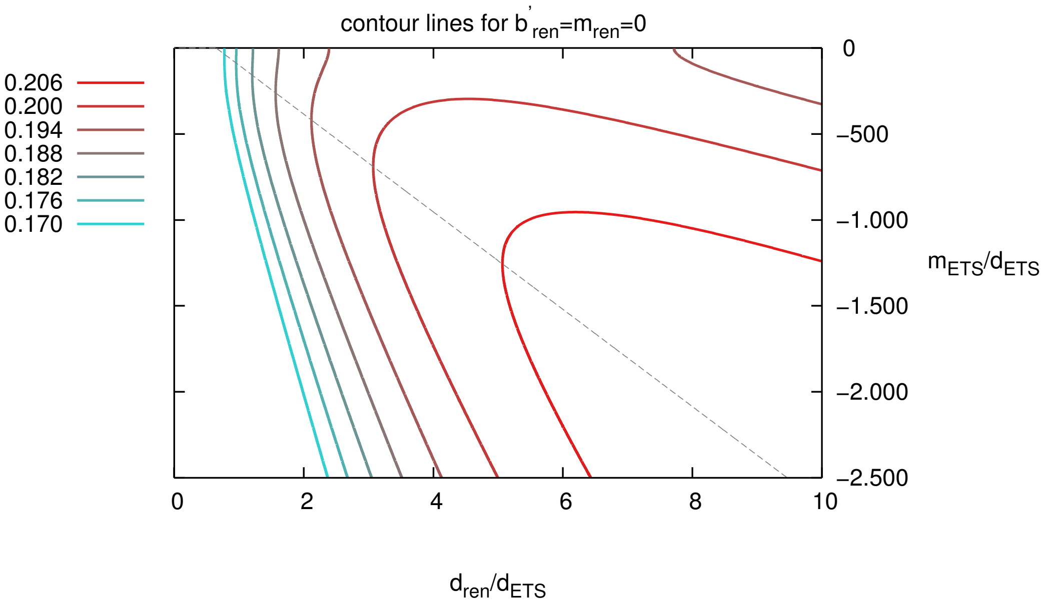

Figure 7: Contour lines of maximum relative additional costs ΔC^{rel} for quadratical MAC. The dashed line indicates the path of maximum relative additional costs.

B Empirical data and calculations

	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
gross power generation [Twh]										
fossil	375.8	396.4	391.7	394.4	398.2	409.2	395.8	363.4	384.8	377.4
according to EEG	25	28.4	38.5	44	51.6	66.8	71.7	74.9	82.3	102.9
- thereof wind power	15.8	18.7	25.5	27.2	30.7	39.7	40.6	38.5	37.6	48.3
- thereof photovoltaics	0.2	0.3	0.6	1.3	2.2	3.1	4.4	6.6	11.7	19.3
- thereof biomass	2.4	3.5	5.2	7.4	10.9	15.9	18.9	23	25.2	28
CO_2 emissions (fossil) [kt]										
electricity	334924	334793	328914	329047	334924	346221	324275	295056	309778	306057
district heating	27194	37162	38885	35350	33390	34371	33036	32081	35392	32765
VET reports. classifications I – III				376781	378663	383608	366613	336616	355761	349910
coverage [%]				96.71	97.27	99.21	97.46	97.18	97.02	96.83
CO_2 saving [kt]										
fossil	-3626	14665	16401	18648	16121	14522	24654	25310	29454	26651
according to EEG	21259	22876	30806	35016	41416	54162	55710	58372	63455	79557
- thereof wind power	13084	14698	19921	21127	24022	31249	30915	29103	28165	36439
- thereof photovoltaics	135	246	435	995	1737	2419	3368	4967	8747	14586
- thereof biomass	2176	2942	4401	6146	9169	13473	15523	18658	20250	22688
costs [Mio. €]										
fossil				5956	5784	225	8353	4503	4771	4224
according to EEG	1253	1497	2112	2774	3777	5232	6189	7779	9860	13042
- thereof wind power	838	988	1335	1410	1572	2006	2026	1927	1840	2436
- thereof photovoltaics	74	138	255	616	1068	1446	2002	2854	4556	6886
- thereof biomass	131	183	292	491	887	1504	1916	2747	3194	3506
evaluation indicator e_i										
fossil	891	844	839	834	840	844	818	816	806	813
according to EEG	827	823	802	791	775	742	738	731	718	677
- thereof wind power	848	844	830	827	820	801	802	807	809	788
- thereof photovoltaics	881	881	880	879	877	875	873	869	859	844
- thereof biomass	876	874	870	866	858	847	842	834	829	823
costs / $\bar{S}$ [€-Cents/kWh]										
fossil				1.01	0.96	0.04	1.32	0.71	0.74	0.65
according to EEG	0.22	0.26	0.36	0.47	0.63	0.85	0.98	1.23	1.54	1.99
- thereof wind power	0.15	0.17	0.23	0.24	0.26	0.33	0.32	0.3	0.29	0.37
- thereof photovoltaics	0.01	0.02	0.04	0.1	0.18	0.24	0.32	0.45	0.71	1.05
- thereof biomass	0.02	0.03	0.05	0.08	0.15	0.24	0.3	0.43	0.5	0.54

e_0^f [g/kWh]	882
$\bar{S}$ [TWh]	640.4
S_{fos} [TWh]	388.7

Table 1: Own calculations based on Federal Environment Agency (2013); Arbeitsgemeinschaft Energiebilanzen e.V (2013); Statistik der Kohlenwirtschaft e.V. (2013); EEG/KWK-G (2013).