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Reconciling Emissions Trading and the Promotion of Renewable Energy

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Abstract

The EU emissions trading system (ETS) and the promotion of renewable energy are overlapping regulations. Although the resulting early development of renewables is associated with several advantages such an overlap may violate the path of optimal abatement. Subsidies may cause a too high share of renewables in electricity generation. This results in additional expenses and efficiency losses. We develop a control mechanism serving as thumb rule to limit additional expenses. Under optimal implementation the rule significantly restricts additional expenses to a maximum of about 4 % of total abatement costs in worst case. This result holds for marginal abatement costs (MAC) approximated by any conical combination of weak convex power functions. This means high flexibility of MAC leading to high validity of the results. Consequences of a non-optimal implementation of the mechanism are examined as well. An empirical application to German data shows that the promotion of renewable energy has not yet violated the path of optimal abatement. However, data is restricted because the ETS has not induced an additional emission reduction since 2010.

Keywords Overlapping Regulations, Promotion of Renewable Energy, Emissions Trading

JEL D61, H23, Q42, Q48, Q54

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1 Introduction

The EU has agreed to cut greenhouse gas emissions until 2050 by an average of 80 – 95 % with respect to the 1990 reference year to mitigate anthropogenic climate change (Council of the EU, 2009). Electricity generation is of particular interest in this context because a big part of emissions is originated here. On the one hand the electricity sector is included in an emissions trading system (ETS) which prices CO_2 emissions. On the other hand the promotion of electricity generation based on renewable energy sources (RES) has been encouraged throughout EU Member States. Both policy instruments are aimed at the reduction of CO_2 emissions.

There is a plenty of literature addressing such overlapping regulations. Already Tinbergen (1952) stated in his seminal work that the treatment of n policy objectives with more than n policy instruments may lead to an inefficient solution. With respect to CO_2 mitigation Nordhaus (2009) points out that the adequate pricing of CO_2 emissions is a sufficient climate policy. Pethig and Wittlich (2009) argue that subsidizing RES simultaneously to an ETS with its binding emission cap will not contribute to emission reduction at all. Others also find a loss in cost efficiency caused by an overlap of the two policy instruments (e.g. Jensen and Skytte, 2003; Böhringer *et al.*, 2009; Böhringer and Rosendahl, 2010). The promotion of RES means for instance a shift of investments to an early stage causing additional costs because of the discounting effect. However, Schäfer (2018b) argues that subsidizing RES lowers depreciation costs of fossil power plants. According to the model, this can already overcompensate additional costs stemming from the discounting effect. Assuming efficient promotion of RES there are still two main problems causing an efficiency loss.

First, a promotion of RES increases uncertainty. The substitution of fossil by renewable electricity generation affects the certificate price and thus the potential of the ETS to reduce CO_2 emissions. In order to set an optimal objective for emission reduction, the regulator requires to perfectly foresee and consider the development of renewable electricity generation. A non-optimal emission cap causes additional costs. However, this argumentation is not totally valid anymore in case of the EU after a mechanism to withdraw excessive certificates from the market was installed (European Parliament and Council of the EU, 2018). Moreover, Schäfer (2018a) suggests the introduction of a unilateral flexible cap which allows to decouple the promotion of renewable energy from the ETS. Then a substitution of fossil electricity generation by subsidized RES does not affect the cap anymore.

Second, a promotion of RES might lead to an exceedance of the optimal share of RES-based power plants (Böhringer *et al.*, 2009). Efficiency gains of fossil electricity generation are physically limited. Therefore, the achievement of ambitious long-run objectives for emission reduction with lowest cost will anyway require a partial switch from fossil to renewable electricity generation[1]. This results in a certain optimal share of renewable electricity generation when the long-run reduction objective is achieved. As long as the share of RES does not exceed this optimal share, the promotion of RES means an early investment which anyway would have been necessary in the future. Unfortunately, the regulator does not know this optimal share of RES. A serious forecast is virtually impossible because the optimal share depends on many future developments. A permanent promotion of RES can thus easily create a share of renewable-based electricity which is too high and thus not optimal. This means additional costs.

We develop a thumb rule which avoids a too high share of electricity generated by promoted RES. The rule does not forecast the optimal share of renewables but continuously evaluates if the optimal share has already been exceeded. This implies an adjustment to a changing environment. The continuous evaluation of the optimal share is based on a comparison of internalized costs induced by the ETS and abatement costs attributed to the promotion of RES.

The thumb rule can significantly reduce a possible excess of renewables' optimal share. Under optimal implementation additional expenses caused by a non-optimal share of RES, even in worst case, do not exceed about 4 % of total abatement costs. This result holds for marginal abatement cost (MAC) approximated by any conical combination of weak convex power functions. This means high flexibility of MAC leading to high validity of the result.

To our knowledge, we are the first presenting such an approach tailor-made for a promotion of RES simultaneously to an ETS. Implementation of the thumb rule does not require a complex calibration. For Germany necessary data is already available in today's reporting obligations. This allows an easy implementation.

The thumb rule reduces disadvantages of subsidized RES while advantages remain. Sorrell and Sijm (2003); Edenhofer *et al.* (2012) for instance point at learning effects of renewables which may eventually decrease total abatement costs. The promotion of RES may also prevent a technological lock-in of mitigation strategies as a result of existing dominant technologies (Unruh, 2000). The thumb rule may thus bring a valuable contribution to develop an effective policy mix for CO_2 abatement. How the welfare-maximizing abatement path will look like, if learning effects and depreciation

[1]RES are the most promising substitute for fossil power plants since they face lower marginal abatement costs (MAC) when compared to nuclear power plants with modern safety requirements or carbon capture and storage (Schröder *et al.*, 2013).

of fossil power plants are considered, is left for further research.

In Section 3.3 we apply the thumb rule to data from Germany as an example. Assuming an efficient promotion scheme for RES we find that the share of renewable energy has not violated the path of minimum costs. Unfortunately, the malfunctioning EU ETS limits the information value of German data applied to our model.

2 Model

The electricity generation of an economy in the business as usual scenario results in a specific emission level E''. With the introduction of an ETS on the way to the long-run objective E^* short-term goals for emission reduction $E' < E''$ are set which limit the number of available allowances.

In the following analysis we assume a perfect ETS which means the certificate price $p(E)$ corresponds to marginal abatement cost (MAC). The certificate price values the abatement of CO_2 which depends on the CO_2 reduction objective E'. According to e.g. Nordhaus (1991) an exacerbation of the emission cap E' leads to lower emissions E but a higher certificate price respectively marginal abatement costs. This yields

$$\frac{\mathrm{d}MAC(E)}{\mathrm{d}E} = \frac{\mathrm{d}p(E)}{\mathrm{d}E} < 0. \tag{1}$$

A perfect ETS reduces CO_2 with lowest MAC while other policy instruments may reveal higher MAC. Böhringer *et al.* (2009) for instance separate MAC which are either assigned to the ETS or not. We use an analogous approach and assume that emission reduction in electricity generation is either induced by the ETS or the subsidization of RES. Therefore, we distinguish MAC_{ets} which is assigned to the ETS and MAC_r which is assigned to the promotion of RES.

Low intermediate objectives for emission reduction can be achieved with low cost by relatively simple modifications of fossil electricity generation. MAC_{ets} is much lower than MAC_r. In this situation the ETS does not induce the substitution of fossil electricity generation by RES. The market entry of RES requires an additional promotion of RES.

This situation changes for tighter emission caps. The reduction potential of fossil electricity generation is physically limited, while the potential of renewable electricity generation exceeds demand. Thus, we can reasonably assume MAC_{ets} increases more than MAC_r with a tightening of the emission cap (see Fig. 1 for illustration). Recalling that increasing MAC means a negative slope with respect to emissions these considerations yield

$$\frac{\mathrm{d}MAC_r(E)}{\mathrm{d}E} \geq \frac{\mathrm{d}MAC_{ets}(E)}{\mathrm{d}E}. \tag{2}$$

Inequality 2 does not specify whether MAC$_r$ is decreasing or increasing with an exacerbation of the emission cap. In general both is conceivable. On the one hand economies of scale and learning effects can be realized leading to decreasing MAC$_r$. These effects are higher for young technologies such as renewable energy (Schröder *et al.*, 2013). On the other hand an increased intermittent electricity generation of renewable energy causes additional costs which may altogether lead to increasing MAC$_r$.

The integral of MAC over mitigated emissions yields abatement costs. Abatement costs to achieve the emission target $E^{'}$ with a perfect ETS (MAC$_{ets}(E)$=$p(E)$) reveal

$$C_{ets}(E^{''} - E^{'}) = \int_{E^{'}}^{E^{''}} p(E)\mathrm{d}E \tag{3}$$

with mitigated emissions corresponding to $E^{''} - E^{'}$. In analogy to Eq. 3 we can also calculate abatement costs in the case of emission reduction by a substitution of fossil by renewable electricity generation

$$C_r(E^{''} - E^{'}) = \int_{E^{'}}^{E^{''}} MAC_r(E)\mathrm{d}E. \tag{4}$$

The integral of MAC from zero to the current emission cap $E^{'}$ yields abatement costs which would be required to mitigate all remaining emissions. These costs are assigned to external costs without emissions trading

$$C_{ext}(E^{'}) = \int_{0}^{E^{'}} p(E)\mathrm{d}E. \tag{5}$$

The product of certificate price and allowed emissions yields the part of external costs, which is already internalized by the ETS because of the emission target $E^{'}$

$$C_{int}(E^{'}) = p(E^{'})E^{'}. \tag{6}$$

2.1 Linear MAC

As first intermediate step of the analysis we assume linear MAC

$$MAC_r(E) = -d_r E + b_r \tag{7}$$

$$MAC_{ets}(E) = -d_{ets} E + b_{ets} \tag{8}$$

with d_r=0 reflecting constant MAC$_r$. b_{ets} is equal to $d_{ets}E^{''}$ to ensure MAC$_{ets}(E^{''}) = 0$ (see Fig. 1 for illustration). In the following we stepwise relax assumptions.

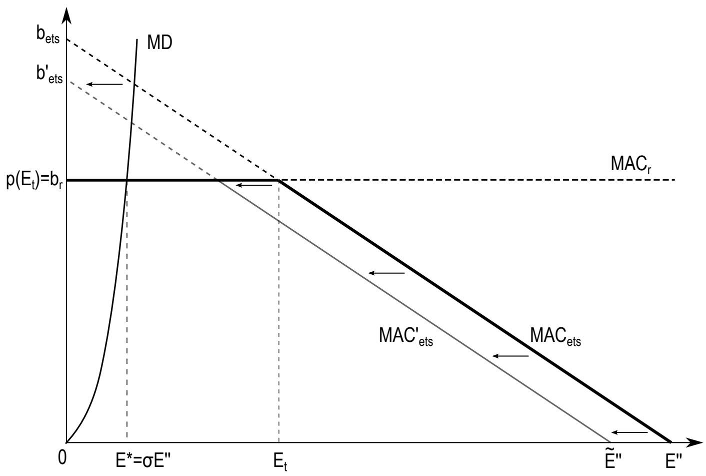


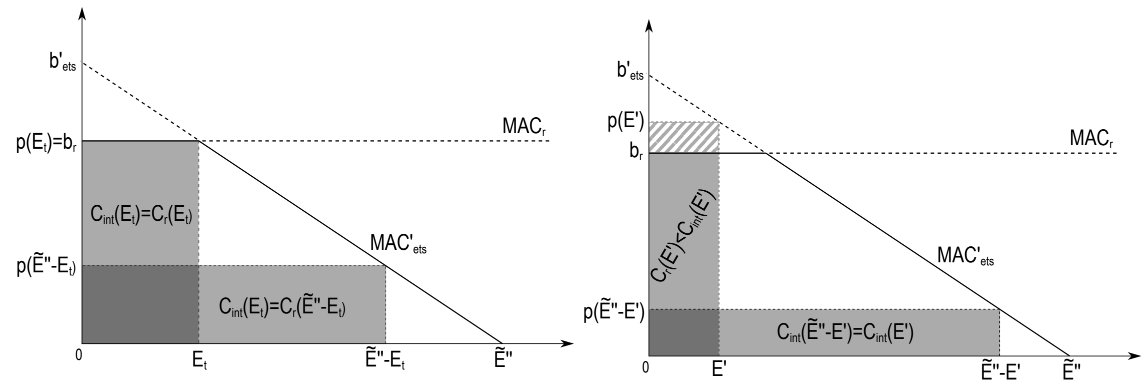
Figure 1: Schematic depiction of MAC consisting of constant MAC$_r$ and linearly increasing MAC$_{ets}$. The solid line reflects the path of lowest MAC while the dashed lines indicate the further course of MAC$_r$ and MAC$_{ets}$. The intersection of MAC and marginal damage (MD) determines the optimal long-run emission level E^*. $E^{''}$ reflects emissions in the business as usual scenario and $\sigma E^{''} = E^*$ the optimal residual of emissions in the long run. $\tilde{E}^{''} := (1-\sigma)E^{''}$ reflects effective emissions which correspond to the necessary long-run reduction. The turning point of mitigation strategies (turn from MAC$_{ets}$ to MAC$_r$) is given by E_t.

The optimum long-run emission level E^* is determined by equality of MAC and marginal damage (MD). Usually E^* is expressed as remaining share σ of initial emissions $E^{''}$. In our model the effect of remaining emissions $\sigma E^{''}$ is modeled by cutting $E^{''}$ and b_{ets} by this amount leading to effective emissions $\tilde{E}^{''} := (1-\sigma)E^{''}$ (see Appendix A.1, Eq. 35). This means a shift of MAC$_{ets}$ to the left exactly by $\sigma E^{''}$ leading to

$$MAC^{'}_{ets} = -d_{ets} E + b^{'}_{ets} \tag{9}$$

as indicated in Fig. 1. In the following we restrain to effective emissions. The consideration of remaining emissions is not necessary allowing a simplification of the illustration as depicted in Fig. 2.

The path of lowest MAC consists of both MAC$_r$ and MAC$_{ets}$. It is illustrated by the solid line in Fig. 1 and 2. Following this path from $\tilde{E}^{''}$ to full abatement of effective emissions leads to a sequence of two mitigation phases. From initial emissions $\tilde{E}''$ to the intersection point of MAC curves E_t we must follow MAC$_{ets}$. Then MAC$_r$ is the optimum strategy (solid line in Fig. 2). Emission reduction at lowest cost do not require a substitution of fossil-based electricity generation for abatement from $\tilde{E}''$ until the turning point E_t (phase 1), while further reductions need such substitution (phase 2). Since a perfect ETS always follows lowest MAC, it induces the described sequence of mitigation phases leading to an optimal mitigation strategy under the assumption of static MAC. For the following analysis we assume no change of MAC$_r$ depending on whether there is a promotion of RES or not. That means to assume an efficient promotion of RES and to neglect dynamic effects (e.g. learning effects).



(a) The shaded area which reaches MAC$_r$ intuitively illustrates equality of $C_r(E_t)$ and $C_{int}(E_t)$. According to the intercept theorem $\frac{p(E_t)}{p(\tilde{E}''-E_t)} = \frac{\tilde{E}''-E_t}{E_t}$, the shaded area which includes MAC$_{ets}(\tilde{E}'' - e_t)$ is also equal to the first shaded area illustrating the equality of $C_{int}(E_t)$ and $C_{int}(\tilde{E}'' - E_t)$.

(b) The shaded area which reaches MAC$_r$ corresponds to $C_r(E')$ while $C_{int}(E')$ additionally includes the crosshatched area. Thus, $C_r(E')$ is smaller than $C_{int}(E')$. In analogy to Fig. 2a the second shaded area which includes MAC$_{ets}(\tilde{E}'' - e_t)$ illustrates equality of $C_{int}(E')$ and $C_{int}(\tilde{E}'' - E')$.

Figure 2: Schematic depiction of linear MAC with constant MAC$_r^{'}$ after shifting MAC$_r$ to the left by $\sigma E''$ as indicated by the arrows in Fig. 1. The solid line again reflects the abatement path with lowest MAC.

Nevertheless, subsidizing renewable energy in addition to the ETS may still lead to a deviation from CO_2 abatement with lowest MAC because the turning point E_t is not known in reality as it depends on various effects (e.g. technological development). Therefore, the promotion of RES could substitute more fossil-based power plants than necessary in the optimum. That is emission reduction with substitution of fossil power plants exceeds E_t. This leads to additional abatement costs. Referring to Fig. 2, this non-optimal scenario would mean to leave the solid line in order to follow MAC$_r$ beyond E_t although MAC$_{ets}$ is lower.

To avoid this non-optimal scenario we do not necessarily need to forecast E_t. It is sufficient to find an approach which allows to estimate if emission reduction induced by the promotion of RES exceeds E_t. Indeed, the turning point is not only determined as intersection of MAC$_r$ and MAC$_{ets}$. It is also determined by equality between abatement costs C_r for emission reduction by RES and C_{int} reflecting future abatement costs which are internalized by the ETS (see Figure 2a for illustration). Under consideration of Eq. 5 and 6 this yields

$$\begin{aligned} \int_0^{\tilde{E}_t} MAC_r(E)\mathrm{d}E &= p(\tilde{E}_t) \cdot \tilde{E}_t \\ \Rightarrow C_r(\tilde{E}_t) &= C_{int}(\tilde{E}_t) \end{aligned} \tag{10}$$

with $\tilde{E}_t = E_t$ for constant MAC$_r$ ($d_r = 0$), while $\tilde{E}_t \neq E_t$ occurs for non-constant MAC$_r$ (see Section 2.2).

If an emission cap limits emissions to less than E_t, MAC$_{ets}$ will always exceed MAC$_r$ (see Fig. 2b for illustration). This yields

$$\begin{aligned} &\int_0^{E'} MAC_r(E)\mathrm{d}E < p(E') \cdot E' \\ \Rightarrow &C_r(E') < C_{int}(E') \qquad \forall E' < \tilde{E}_t. \end{aligned} \tag{11}$$

Eq. 10 and Inequality 11 are not directly exploitable. So far C_r and C_{int} are both evaluated for the abatement of emissions from $\tilde{E}_t$ to zero respectively from E' to zero.

However, we do not have to abate two times $\tilde{E}'$ or E' but eventually complete effective emissions $\tilde{E}''$ till zero. Thus, referring to Fig. 2, Eq. 10 and Inequality 11 are only useful if C_{int} and C_r refer to different sectors below the MAC curve The necessary rearrangement of Eq. 10 and Inequality 11 is possible using the intercept theorem which yields $\frac{p(E_t)}{p(\tilde{E}''-E_t)}$ is equal to $\frac{\tilde{E}''-E_t}{E_t}$ leading to $C_{int}(\tilde{E}'' - \tilde{E}_t) = C_{int}(\tilde{E}_t)$ (see Figure 2b). This allows to rewrite Eq. 10 and Inequality 11 yielding

$$\begin{aligned} C_r(\tilde{E}_t) &= p(\tilde{E}'' - \tilde{E}_t) \cdot (\tilde{E}'' - \tilde{E}_t) \\ &= C_{int}(\tilde{E}'' - \tilde{E}_t) \end{aligned} \tag{12}$$

and

$$\begin{aligned} &\int_0^{E'} MAC_r(E)\mathrm{d}E < p(\tilde{E}'' - E') \cdot (\tilde{E}'' - E') \\ \Rightarrow &C_r(E') < C_{int}(\tilde{E}'' - E') \qquad \forall E' < \tilde{E}_t. \end{aligned} \tag{13}$$

For linear MAC there is no difference in using Eq. 10, Inequality 11 or Eq. 12, Inequality 13. However, the interpretation is different.

Referring to Figure 2a, Eq. 12 means emission abatement starts at $\tilde{E}''$ if induced by the ETS while abatement starts at E_t if induced by the promotion of RES. From these starting points emissions are simultaneously reduced following the abscissa to the left until $\tilde{E}'' - E_t$ is reached in case of the ETS, while zero is reached in case of subsidized RES. Eventually, both policy instruments lead to an emission reduction amounting to $\tilde{E}''$ but referring to different sectors below the MAC curve.

Inequality 13 shows an analogous behavior. Subsidized RES reduce emissions from E' to zero while the ETS reduces emissions from $\tilde{E}''$ to $\tilde{E}'' - E'$ (see Fig. 2b). On the one hand the amount of emission reduction is exactly equal for both, the promotion of RES and the ETS. On the other hand emission reduction is assigned to different sectors of the MAC curve now. That means Eq. 12 and Inequality 13 compare C_r and C_{int} for equal emission reduction assigned to different sectors of the MAC curve.

Now the relation between C_{int} and C_r delivers a valuable information. For illustration let us assume a situation in which ETS and promotion of RES induce equal emission abatement. Then we know that, according to the model, the share of RES-based electricity generation does not exceed the optimal share as long as Inequality 13 holds. In this case a further promotion of RES does not violate the path of minimum costs. As soon as E' exceeds E_t Inequality 13 is inverted to $C_r(E') > C_{int}(\tilde{E}'' - E')$.

This allows a regulation strategy which accounts for the promotion of renewable energy simultaneously to the ETS if the regulator follows the following three steps. First, the regulator should try to achieve a preferably equal emission reduction with each of the two policy instruments, the ETS and the promotion of RES.[2] Second, the regulator compares abatement costs C_r induced by renewables and costs C_{int} which are internalized by the ETS according to Inequality 13. As long as internalized costs of the ETS C_{int} exceed renewables' abatement costs C_r, a further promotion of RES does not violate the path of minimum costs. Third, the regulator should modify (respectively stop) the promotion of renewable energy if the inequality merges into equality (Inequality 13 turns into Eq. 12). This control mechanism can eliminate efficiency losses caused by a too high share of renewable-based power plants for linear MAC with constant MAC_r. For increasing MAC_r or non-linear MAC with convex shape it is a good thumb rule which significantly reduces efficiency losses (see Sections 2.2 and 2.3).

[2]If emission reductions of the two policy instruments are not equal the control mechanism will not be optimally implemented. Nevertheless it is applicable while resulting inaccuracies increase (see Section 2.2 and Fig. 5).

2.2 Worst-case analysis

In the next step of analysis we maintain linear MAC but keep MAC_r no longer constant ($d_r \neq 0$) to relax assumptions. The situation with increasing MAC_r is depicted in Fig. 3. However, the presentation, in comparison to Fig. 2, needs a modification to fulfill the rule of zero arbitrage[3]

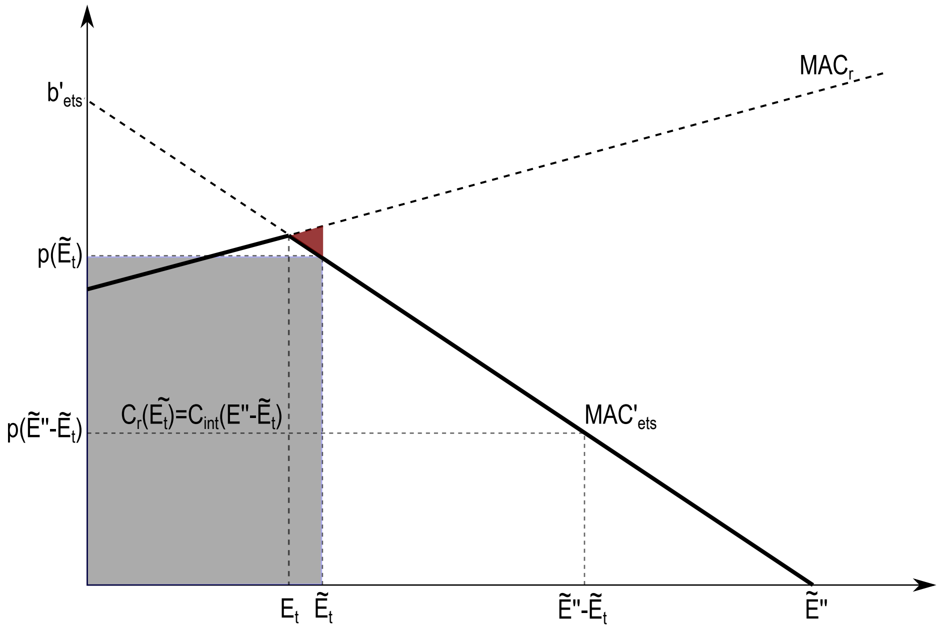


Figure 3: Schematic depiction of linear MAC with increasing MAC_r. Emissions increase from right to left with respect to MAC_r while they increase from left to right with respect to MAC_{ets}. $\tilde{E}^{''}$ corresponds to effective emissions in the business as usual scenario. The real turning point of mitigation strategies is given by E_t. The turning point which is calculated on the basis of Eq. 11 is $\tilde{E}_t$. The deviation of calculated and real turning point results in additional costs ΔC (filled triangle).

In contrast to Fig. 1 and 2 abatement now starts at zero and intensifies to the right for MAC_r. The resulting modification of Eq. 7 is

$$MAC_r^{'}(E) = d_r E + b_r^{'} \tag{14}$$

with $b_r^{'} = b_r - d_r E_t$. $b_r^{'}$ corresponds to initial MAC_r which is identifiable in reality, while $b_{ets}^{'}$ reflects MAC_{ets} after complete abatement of effective emissions without RES. This final value for MAC_{ets} is unknown. As discussed above we assume the necessity of RES to achieve the long-run objective for emission reduction. Thus, initial MAC_r must be lower than final MAC_{ets} leading to

$$b_{ets}^{'} \geq b_r^{'} \geq 0 \tag{15}$$

[3]If emissions are reduced by $\tilde{E}^{''}$ a stable equilibrium requires equality of MAC_r and MAC_{ets} since otherwise there is an incentive to change the share of electricity generated by RES.

as additional constraint.

As a consequence of the modified presentation in Fig. 3 an optimal promotion of RES ends, as well as emission abatement by the ETS, in the turning point E_t. This means equality of MAC_r and MAC_{ets} in the long run. This property is fulfilled in Fig. 1 without inversion of the abscissa for MAC_r because of constant MAC_r.

If the regulator uses the control mechanism which is described in Section 2.1 he or she will stop subsidizing RES when, based on equal emission abatement, C_r equals C_{int}. That is to use Eq. 10 (or Eq. 12) to determine the turning point which yields

$$\tilde{E}_t = \frac{b'_{ets} - b'_r}{\frac{1}{2}d_r + d_{ets}}, \tag{16}$$

while the real turning point is determined by MAC'_r=MAC_{ets} yielding

$$E_t = \frac{b'_{ets} - b'_r}{d_r + d_{ets}}. \tag{17}$$

According to Eq. 16 and 17, E_t equals $\tilde{E}_t$ for constant MAC_r ($d_r = 0$) whereas we find a deviation for non-constant MAC_r ($d_r \neq 0$). The deviation of $\tilde{E}_t$ from the real turning point E_t means an early stop for decreasing MAC_r ($d_r < 0$) and a too long promotion in the case of increasing MAC_r ($d_r > 0$). The early stop will be "corrected" after some time when increasing MAC_{ets} reaches the level of MAC_r. An early stop might reduce the positive effect of subsidizing RES (e.g. learning effects) but it does not create additional costs because the turning point is exceeded by abatement with RES. In contrast, a too long promotion means additional abatement costs ΔC (see red triangle in Fig. 3) leading to an efficiency loss of abatement. Thus, the following worst-case analysis only accounts for increasing MAC_r to estimate the possible maximum of relative additional costs of a late stop of subsidies for RES.

Let us assume that the regulator follows our control mechanism and stops subsidizing RES when Inequality 11 turns into Eq. 10. This allows to calculate total abatement costs ($C_r + C_{ets}$) and additional abatement costs ΔC caused by the displace of $\tilde{E}_t$ when compared to E_t. Using $\delta := \frac{d_r}{d_{ets}}$ and $\beta := \frac{b'_r}{b'_{ets}}$ the ratio of additional and total abatement costs $\frac{\Delta C}{C}$ yields relative additional abatement costs (see Appendix A.1 for detailed calculations)

$$\Delta C_{rel} = \frac{\delta^2(1-\beta)^2}{4(\delta+1)(\frac{1}{4}\delta^2 - \beta^2 + \delta + 2\beta)}. \tag{18}$$

To evaluate the control mechanism in a worst case scenario we maximize Eq. 18 with respect to δ and β. Considering constraints given in Inequalities 2 and 15 we find a maximum of $\Delta C_{rel} = \frac{1}{10}$ for $\beta = 0$ and $\delta = 1$ (see Appendix A.1 for details). A very low β converging to zero corresponds to $b_{ets} \gg b_r$, which is plausible with respect to the limited potential of emission savings within the fossil sector. This means additional abatement costs, caused by promotion of RES in addition to an ETS, have a share of 10 % of total abatement costs at the worst. At lower slope ratios δ, relative additional costs decrease accordingly (see lower dashed line in Fig. 4).

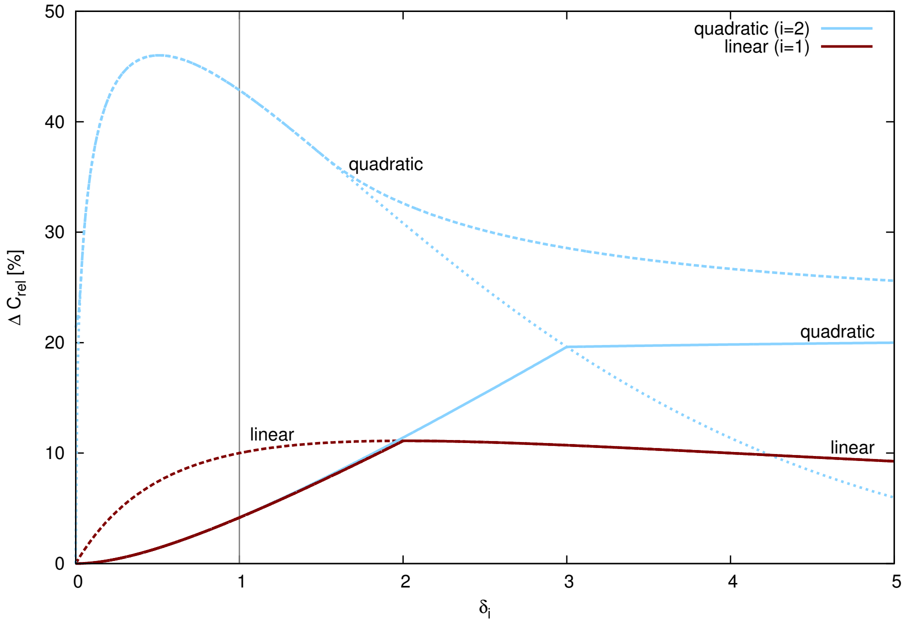


Figure 4: Evolution of relative additional costs ΔC_{rel} with linearly (dark red) and quadratically (bright blue) rising MAC. ΔC_{rel}, $\tilde{E}_t$ and E_t can be calculated analytically for linear quadratic MAC. Dashed lines indicate $\beta = 0$ while solid lines are the result of $\beta = \frac{2-\delta}{4}$. For quadratic MAC two dashed curves are illustrated. The lower curve corresponds to the situation without linear term ($d_{1,ets} = 0$), while the upper one is the result of $d_{1,ets}$ chosen to maximize ΔC_{rel}. According to Eq. 2 only the part left to the vertical line is relevant.

However, this result does not take into account that perfect implementation of the control mechanism compares internalized costs C_{int} and abatement costs for RES C_r on the basis of exactly equal emission reductions for both policy instruments. Therefore, an optimal implementation of the mechanism a priori restricts abatements for renewables to half of total emissions to be mitigated $(\frac{\tilde{E}''}{2})$.[4] Additional costs may only occur if $E_t < \frac{\tilde{E}''}{2}$. Taking into account $\delta \leq 1$ as plausible constraint (see Inequality 2), $\beta = 0$ would lead to $E_t \geq \frac{\tilde{E}''}{2}$ which would mean no additional costs. For perfect implementation of the control mechanism relative additional abatement costs are consequently maximized for $\beta > 0$. We find a maximum if β leads exactly

[4]If the optimal abatement strategy leads to a higher share of RES-based electricity generation, MAC_{ets} will be equal to MAC_r before the turning point is reached.

to $\tilde{E}_t = \frac{\tilde{E}''}{2}$ (see Appendix A.1.1 for proof). To calculate this maximizing β we insert $\tilde{E}_t = \frac{\tilde{E}''}{2}$ in Eq. 16 leading to $\beta = \frac{2-\delta}{4}$. For the maximum condition $\delta = 1$ we obtain $\beta = 0.25$ leading to

$$\max_{\beta,\delta} \Delta C_{rel} = \frac{1}{24} \qquad \forall 0 \leq \beta \leq \frac{2-\delta}{4} \wedge 0 \leq \delta \leq 1 \tag{19}$$

for perfect implementation of the control mechanism (see also solid dark red line in Fig. 4). This is a rather low value for a worst case scenario. Thus, the control mechanism is a good thumb rule to coordinate a promotion of RES simultaneously to the ETS if we assume perfect implementation and linear MAC.

However, relative additional costs may increase if the control mechanism is not optimally implemented. That happens if emission reduction induced by the promotion of renewable energy exceeds reductions induced by the ETS. Let us assume promoted RES achieves an emission abatement which exceeds the emission abatement induced by the ETS for example by $x \cdot \tilde{E}''$. Then x corresponds to the share of total effective emissions $\tilde{E}''$ mitigated by renewables in advance when compared to the ETS. Then CO_2 mitigation by renewables is no longer limited to $\frac{\tilde{E}''}{2}$ but to $\frac{\tilde{E}''}{2}(1+x)$ instead. Reasons for the advance in emissions abatement may be an ETS which is not properly working or subsidies for renewables which are too high. In this case relative additional costs are maximized if β results in $\tilde{E}_t = \frac{\tilde{E}''}{2}(1+x)$. Inserting this into Eq. 16 obtains

$$\beta = \frac{2-\delta}{4} - \frac{2+\delta}{4}x \tag{20}$$

as additional constraint while β is restricted to positive values (see Inequality 15). As stated above a perfect implementation of the control mechanism ($x = 0$) leads to $\beta = 0.25$ if the corner solution $\delta = 1$ is considered.

According to Eq. 20, a non-optimal implementation of the control mechanism ($x > 0$) results in a lower β eventually leading to higher relative additional costs. The higher x, the less is controlled for an efficient coordination of renewables' promotion and the ETS. Relative additional costs can significantly exceed the maximum value $\frac{1}{10}$ because the long-run share of renewables will equal at least to x although $\tilde{E}_t$ might be lower. That is the reason why there is a massive increase of ΔC_{rel} for linear MAC with $x > 1/3$ (see lower line in Fig. 5 and Appendix A.1.1 for details).

The preceding analysis reveals one main benefit of the described control mechanism. In contrast to a forecast of E_t, uncertainty about MAC yields quantifiable extra cost which are low even in a worst-case scenario. Since the mechanism underlies a recurring process, it considers that MAC is not static. Moreover, both, internalized costs of the

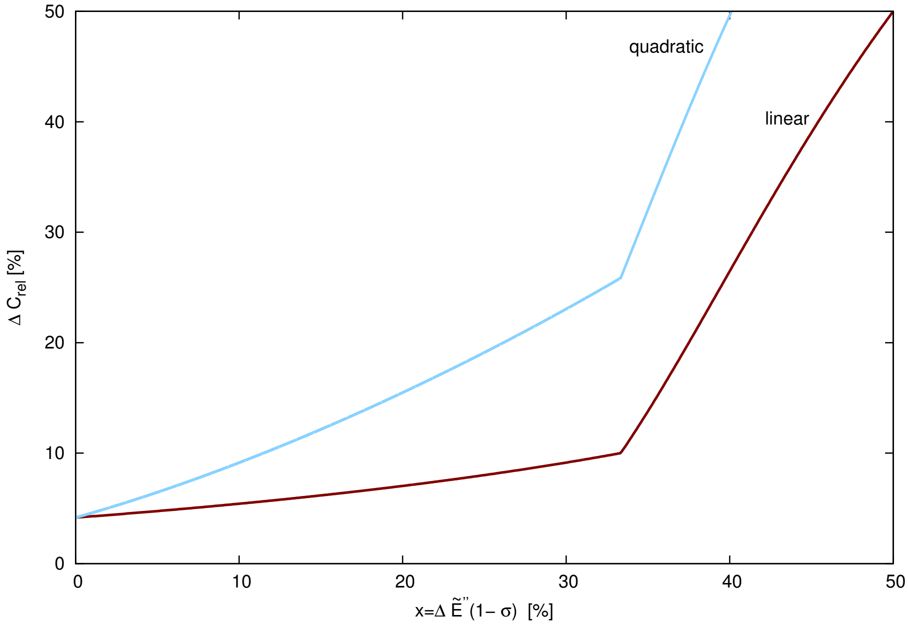


Figure 5: Relative additional costs ΔC_{rel} for linear and quadratic MAC under suboptimal implementation of the control mechanism in the worst case scenario ($\delta = 1$). Relative additional costs increase with the share $x = \Delta\tilde{E}''(1-\sigma)$ of renewables' mitigation in advance to the ETS.

ETS and renewables' abatement costs are already available data. Thus, the mechanism is rather easy to implement (see Section 3).

2.3 MAC as conical combination of power functions

Although linear MAC is a common assumption in environmental economics, an expansion to convex MAC would be a benefit. For high mitigation levels convex MAC are likely because the emission reduction of fossil electricity generation reaches physical limits. Moreover, a high share of renewables may lead to a disproportional higher increase of balancing costs caused by intermittent electricity generation. This may justify convex MAC$_r$ for a high share of RES. A conical combination[5] of power functions in accordance to Eq. 9 and 14 yields

$$\begin{aligned} MAC_r'(E) &= \sum_i^n (d_{r,i}E^i + b_{r,i}') \\ MAC_{ets}'(E) &= \sum_i^n d_{ets,i}(\tilde{E}'' - E)^i \qquad \forall i \in \mathbb{R} \geq 1 \end{aligned} \tag{21}$$

[5]A conical combination is a non-negative linear combination

Moreover, we redefine Inequality 15 resulting in

$$b'_{ets,i} \geq b_{max,i} \geq b'_{r,i} \geq 0 \tag{22}$$

with $b_{max,i}$ defining the maximal value for $b'_{r,i}$ which still allows the calculation of the estimated turning point $\tilde{E}_t$.

Fortunately, Inequality 22 is only a theoretical restriction with very limited effect in reality. In the initial period of emission abatement linear MAC can be expected (see e.g. our analysis for Germany in Section 3.3). Then there is no additional restriction by Inequality 22 because $b_{max,i}$ is equal to $b'_{ets,i}$ in this case. Convex MAC can be reasonably expected for MAC$_{ets}$ in the later process of emission reduction as result of physical limitations of abatement in the fossil sector. This would lead to a sharp increase of final MAC$_{ets}$ resulting in high $b'_{ets,i}$ while initial MAC$_r$, reflected by $b_{r,i}$, is not affected. Thus, we can reasonably assume a decreasing ratio of $b'_{r,i}$ and $b'_{ets,i}$ the more convex the shape of MAC is. There is also no evidence that Inequality 22 is a binding restriction with respect to real data as described for Germany in Section 3.3.

As discussed in Section 2.2 the implementation of the control mechanism a priori restricts emission reduction for promoted renewable energy to $\frac{\tilde{E}''}{2}(1+x)$. Taking this into account, relative additional costs ΔC_{rel} are maximized for

$$\begin{aligned}
b'_{r,i} &= \sum_{i\geq 1}^{n} \left(\frac{1-x}{1+x} d_{ets,i} - \frac{d_{r,i}}{1+i} \right) \left(\frac{\tilde{E}''}{2} \right)^{i} (1+x)^{i} \\
\Rightarrow \beta_i &= \sum_{i\geq 1}^{n} \left(\frac{1-x}{1+x} - \frac{\delta_i}{1+i} \right) \left(\frac{1+x}{2} \right)^{i}
\end{aligned} \tag{23}$$

using $b'_r := \sum_{i\geq 1}^{n} b'_{r,i}$ for the first line and $b_{i,ets} = d_{i,ets}\tilde{E}''^{i}$, $\beta_i := \frac{b_{i,r}}{b_{i,ets}}$ for the second line of Eq. 23.

Proof: See Appendix A.3.1.

Eq. 23 is a binding constraint for any conical combination of weak convex power functions ($i \geq 1$). Concave functions ($i < 1$) produce discrepant results and will be neglected in the following analysis. This does not lower the significance of the analysis since concave MAC are implausible referring e.g. to physical limitations in emission reduction with fossil electricity generation.

For simplicity in notation we assume $x = 0$ in the following while results also hold for $x \neq 0$. In analogy to linear MAC relative additional costs are maximized for a ratio of coefficients $\delta_i := \frac{d_{i,r}}{d_{i,ets}}$ equal to one.

Proof: See Appendix A.3.2.

Calculating relative additional costs under consideration of Eq. 23 for $\delta_i = 1$ yields (see Appendix A.3.2 for details)

$$\Delta C_{rel} = 1 - \frac{\sum_{i\geq 1}^{n} d_{i,ets}\left[\left(\frac{i}{i+1}\right)\left(\frac{\tilde{E}''}{2}\right)^{i} E_t + \frac{1}{i+1}E_t^{i+1} + \frac{1}{i+1}(\tilde{E}'' - E_t)^{i+1}\right]}{\sum_{i\geq 1}^{n} d_{i,ets}\left(\frac{i+2}{i+1}\right)\left(\frac{\tilde{E}''}{2}\right)^{i+1}}. \tag{24}$$

ΔC_{rel} is maximized if the fraction in Eq. 24 is minimized. Counter and denominator each consist of a summation over i. Such a structure corresponds to the summation of two-dimensional vectors. The resulting vector of a summation of several vectors can never have a higher/lower slope than the highest/lowest slope of a vector the sum consists of. Thus, there is always at least one power function within a conical combination of weak convex power functions which leads to higher relative additional costs than the conical combination as a whole.

Proof: See Appendix A.3.3.

Therefore, it is sufficient to restrict a worst case analysis to power functions which a conical combination consists of. Relative additional costs of the conical combination cannot be higher.

Numerical calculations show that relative additional costs for polynomials ($i \in \mathbb{N}$) never exceed respective costs for linear MAC. Relative additional costs, under perfect implementation of the control mechanism, are thus restricted to a share of about 4.2 % of total abatement costs. For any conical combination of convex power functions with $i \in \mathbb{R} \geq 1$ relative additional costs are only slightly higher and reach a maximum of 4.3 % of total abatement costs for perfect implementation of the control mechanism (see Figure 6).

Pure convex MAC, in contrast to linear MAC, may result in abatement costs of RES $C_r(E^{'})$ which are initially higher than internalized costs of the ETS $C_{int}(E^{'})$. This would appear for a high ratio of initial MAC for renewables and final MAC$_{ets}$ ($b_r^{'}/b_{ets}^{'}$). As discussed above, this scenario is very unlikely because emission reduction within the fossil sector faces physical limitations, whereas such limits do not exist for RES. Therefore, convex MAC are a reasonable assumption for MAC$_{ets}$ with progressive

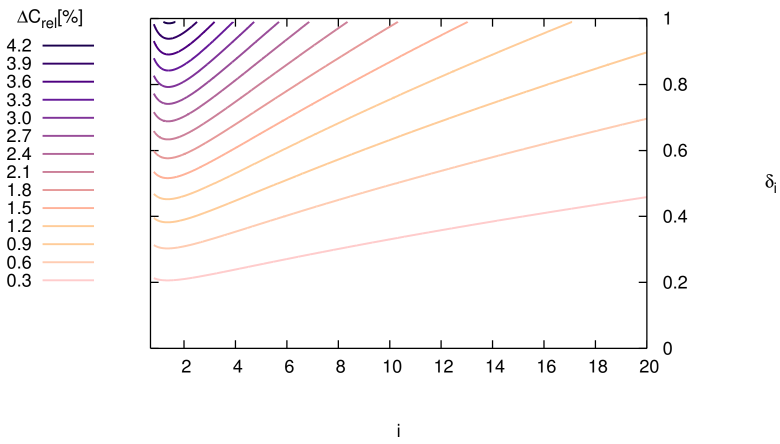


Figure 6: Evolution of relative additional costs ΔC_{rel} for weak convex power functions with $1 \leq i \leq 20$ with δ_i in the relevant range between 0 and 1. E_t and $\tilde{E}_t$ are calculated numerically.

emission abatement which means a correspondingly high $b^{'}_{ets}$ leading to a low ratio $b^{'}_{r}/b^{'}_{ets}$. Ultimately, the suggested control mechanism should not be regarded as an absolute rule but as an indicator which has to be checked for plausibility. Therefore, this restriction does not challenge the expansion of the worst-case analysis to conical combinations of weak convex power functions. Furthermore, application of the thumb rule to German data does not show the described complications (see Section 3.3).

3 Empirical application of the control mechanism

An adequate empirical application of the model requires reliable data for each year i to evaluate success and costs of both ETS and promotion of renewable energy. According to Eq. 6, internalized costs C_{int} can be estimated by the product of the averaged certificate price and generated electricity which is affected by the ETS. Data for certificate price and electricity generation in Germany are available. The same applies for abatement costs C_r which are caused by the promotion of RES (see Appendix B for details about data). While costs can be determined rather easily the attribution of emission reductions is quite difficult.

The requested evaluation indicators must be comparable for both policy instruments. Moreover, they should take into account the production side only. The ETS as well as the promotion of renewable energy mean an internalization of costs if it results in a respective supplement on electricity prices. This price effect creates an additional mitigation of CO_2 emissions by reduced demand. Nevertheless, an efficient mitigation procedure achieves the long-run objective following the path of minimum costs because higher costs are associated with utility losses. Hence, demand-side emission reductions can be neglected.

3.1 Indicator to evaluate the success of the EU ETS

Schäfer (2018a) calculates the emission reduction in the German electricity sector, attributed to the EU ETS, calculated by comparison of emission intensities[6] with a counterfactual scenario without ETS. The analysis is based on a regression considering data for emissions, electricity output and fuel prices between 2000 and 2015. It turns out that a long-time trend and the price ratio between coal and gas allow a good estimate to explain changes in emission intensity ($R^2 = 0.84$). The stronger the long-run time trend, the lower is the impact of the EU ETS. We calculate the counterfactual scenario under consideration of the price ratio for coal and gas without the impact of the EU ETS and chose the lower limit of the calculated range for the long-run trend. All remaining emission reduction is attributed to the ETS. Thus, the counterfactual scenario most probably overestimates the effect of the EU ETS. Following this approach, we obtain for the ETS-induced change in emission intensity $\Delta e_{ets,i}$ and emissions $\Delta E_{ets,i}$

$$\Delta e_{ets,i} = e_i - e_{cf,i} \tag{25}$$

$$\Rightarrow \Delta E_{ets,i} = (e_i - e_{cf,i}) S_{ets,i} \tag{26}$$

with e_i and $e_{cf,i}$ corresponding to measured emission intensity respectively emission intensity of the counterfactual scenario. $S_{ets,i}$ is the ETS-affected electricity output.

However, this approach does not consider imported emission reduction. Imported emission reduction occurs if the ETS leads to a lower electricity generation with emission-intensive power plants in country A while necessary electricity is generated with less emissions in county B and exported to country A. Nevertheless, imported emission reductions can be neglected in our analysis. We want to develop a thumb rule on the national level because each country of the EU has a distinct objective for emission reduction. In addition, there are particularly two reasons why imported emission reductions are anyway limited. First, countries are usually not willing to give

[6] Emission intensity e is defined as emissions E per generated electricity unit S_{ets} in the sphere of the ETS (see Schäfer (2018a) for details). Using emission intensities instead of absolute emissions controls for demand side effects (e.g. business effects).

up the strategic position of an own electricity generation. Second, the interconnection capacity between countries is limited.

Eq. 26 corresponds to the estimated emission reduction caused by the EU ETS. Dividing $\Delta E_{ets,i}$ by the average ETS-affected electricity output of the period of observation $\bar{S}_{ets}$ normalizes the change in emission intensity with respect to generated electricity. Subtracting this normalized change in emission intensity from the emission intensity of a certain base period $e_{\bar{0}}$ defines the normalized emission intensity

$$e_{ets,i} = e_{\bar{0}} - \frac{\Delta E_{ets,i}}{\bar{S}_{ets}} \tag{27}$$

which allows a comparison to the evaluation indicator of renewable energy (see Eq. 29).

3.2 Indicator to evaluate the success of RES

The success of RES, in terms of emission reduction, can only be evaluated relatively to fossil energy. This means the determination of emissions which would have been emitted by fossil fuels if RES-based power plants had not replaced them.

In the short- and medium-run the introduction of renewable energy leads to excess capacity. Since, in particular, solar and wind power have virtually no variable costs, their usages change the merit order of a usual energy-only market. The supply curve shifts to higher capacities and the market price decreases. This effect is known as the merit order effect of RES (Sensfuß *et al.*, 2008). Consequently, in particular fossil power plants with highest variable costs (peak load power plants) are used less.

In the long-run, the fleet of power plants can adapt and the described merit order effect disappears. If a fossil base-load remains necessary to meet demand the result will be a pro rata reduction of fossil capacity (Weber and Woll, 2007). With a further increasing share of renewable energy base-load power plants are affected disproportionately. The longer phases of total renewable electricity supply last, the less base-load power plants are needed. Thus, in particular base-load power plants will be squeezed out of the market in the long-run (Fürsch *et al.*, 2012).

Base-load and peak-load power plants usually differ in emission intensity. If for example base-load power plants (e.g. coal, lignite) are more emission-intensive than peak-load power plants (e.g. gas) the merit order effect at first leads to lower emission reduction than average. If base-load power plants are based on nuclear power-plants we see higher emission reductions at first. Nevertheless, in the medium term there will be a substitution of power plants with average emissions. Finally, in particular, base-load power plants will be substituted. This long-term development is already induced by the current installation of renewable generation capacity. This justifies to take current average emissions of the ETS-affected electricity supply as a basis for emission savings by renewable energy. The temporary merit order effect is neglected in terms of costs and in that of emissions.

The usage of non-adjustable renewables (wind, solar) requires additional expenses for necessary extra balancing energy. According to (Memmler *et al.*, 2009, p. 49), this is taken into account if electricity, which is generated by these renewables, is not fully considered but only to 93 %. In analogy to Eq. 25 this yields

$$\Delta E_{r,i} = e_i S_{r,i} p \tag{28}$$

with $p = 0.93$ for non-adjustable renewables and $p = 1$ for others.

To achieve comparability with the evaluation indicator of the ETS CO_2-savings must be related to the base period of the ETS and expressed relatively to the average electricity generated under the ETS in g/kWh. This yields

$$e_{r,i} = e_{\bar{0}} - \frac{\Delta E_{r,i}}{\bar{S}_{ets}} \tag{29}$$

which is in analogy to Eq. 27.

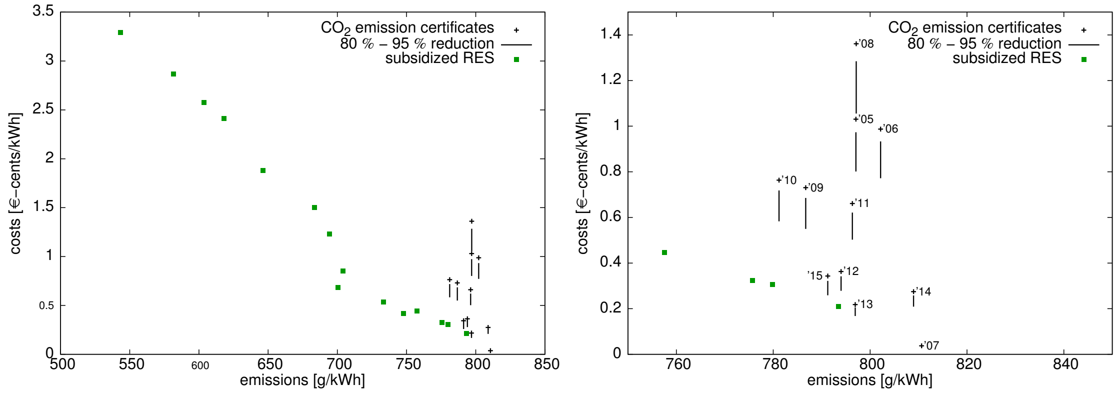
3.3 Results of the empirical application of the model

In order increase the explanatory value of our analysis we do not use the absolute value of annual costs $C_{i,int}, C_{i,r}$ but the ratio between these costs and the averaged total electricity output in the observation period $\bar{S}$ in the following. $C_{i,int}/\bar{S}$ and $C_{i,r}/\bar{S}$ correspond to the theoretical value of consumers' burden caused by the ETS and the promotion of renewable energy.[7] Necessary data for Germany are taken from various sources (see Appendix B for detailed information).

Data analysis of the ETS provides a diffused picture (see Fig. 7). This can be explained at least to a certain degree by different effects. The first trading period for example was marked by massive over-allocation. Nevertheless, market participants were not aware of it until the publication of the first emission data by EU Member States at

[7]The theoretical value equals the actual consumers' burden if two requirements are fulfilled. First, internalized costs of the ETS have to be fully passed on to electricity consumers, for which there is some evidence (Sijm *et al.*, 2006). Second, abatement costs of renewable energy have to be spread to gross electricity generation.

the end of April 2006 (German Emissions Trading Authority, 2009, p. 96). Since the transfer of certificates to the second trading period was impossible, the overallocation led to a market collapse. Thus, the information value for 2007 is highly limited.



(a) full presentation

(b) detail of Fig. 7a

Figure 7: Costs internalized by the ETS C_{int} and abatement costs of renewable energy C_r in relation to average electricity generation $\bar{S}_{ets}$ with respective emission levels in 2010 prices. Costs are given as ratio to averaged total electricity output in the observation period $\bar{S}$. The top of the vertical lines corresponds to adjusted internalized costs of the ETS if 95 % of 1990 emissions shall be mitigated in the long-run. The lower side of the lines illustrates a mitigation of 80 %. Own illustration based on Table 1.

Starting from the end of 2008 the real economy was penetrated by the financial and economic crisis. This resulted in a surplus of about 650 million certificates during the second trading period (Neuhoff and Schopp, 2013). So-called Certified Emission Reductiuons (CERs) and Emission Reduction Units (ERUs)[8] increased the supply of allowances at the beginning of the third trading period of an additional 1.68 billion certificates (Neuhoff *et al.*, 2012). Already these two effects exceed the total anticipated emission reductions of the third trading period (1.95 billion). Compared to the second trading period, up to 2020 no additional savings within the EU are required. In 2015 there was still an excess of 1.78 billion emission certificates (European Commission, 2017). Hardly surprising the ETS did not induce additional emission reductions in the German electricity sector after 2010 (see Fig. 7).

With respect to internalized costs C_{int} there seems to be almost no correlation with emission intensity at first sight (see Fig. 7). This changes a bit if we group data points with respect to the occurrence of oversupply. This yields two groups with different price levels. The group with the high price level contains data of the years 2005 – 2006 and 2008 which are the only years which were not fully affected by oversupply. The group with the low price level consists of remaining data. While there are not enough data points in the high price group internalized costs per kWh seem (more or less) to

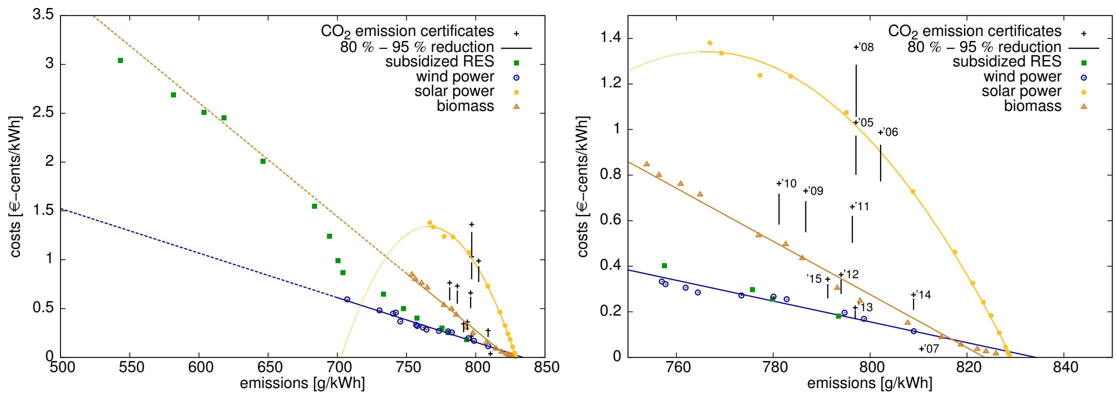
[8]CERs and ERUs allow to get certificates of the EU ETS for emissions abatement outside the EU.

increase with higher abatements in low price group (see Fig. 7). This is a plausible behavior with respect to the broadly accepted assumption of MAC_{ets} increasing with higher abatements.

Beside discussed oversupply of certificates there is another possible reason for the formation of different groups. In contrast to our assumption in the model the certificate price does not exactly correspond to MAC_{ets} in reality. It is also influenced by future expectations of market participants. Different price levels can thus be the result of changed expectations.

In contrast to the ETS renewable energy shows a clear correlation between increased emissions and rising abatement costs. We see a comparatively small increase of costs up to an emission level of about 700 g/kWh followed by a strong one to lower emission levels (see Fig. 7a). Around the mentioned emission level, which was reached in 2006, a massive expansion of solar power began while promoted renewable energy was mostly based on wind power before. Since solar power significantly exceeded generation costs of wind power, it resulted in an increase in the entire costs of renewable energy promotion.

Abatement costs of renewables C_r are the difference of the remuneration paid for renewable electricity and electricity prices at the power exchange. Thus, C_r may also include high profits for operators of RES-based power plants. The regulator must be aware, that this may distort results. C_r is also highly sensitive to electricity prices at the power exchange. Using a constant average electricity price of the observation period instead of the varying true electricity prices eliminates this effect (see Fig. 8).



(a) full presentation

(b) detail of Fig. 8a

Figure 8: Costs internalized by the ETS C_{int} and abatement costs of renewable energy C_r in relation to average electricity generation $\bar{S}_{ets}$ with respective emission levels in 2010 prices under the assumption of a constant average stock market price for electricity. Costs are given as ratio to averaged total electricity output in the observation period $\bar{S}$. The top of the vertical lines corresponds to the adjusted internalized costs of the ETS if 95 % of 1990 emissions shall be mitigated in the long-run. The lower side of the line means a mitigation of 80 %. Own illustration based on Table 1.

Abatement costs of the main components of renewable energy (wind, solar and biomass) are, so far, well-described by linear or quadratic functions. Figure 8 also shows abatement costs if CO_2 reduction took place solely with each of these three components. In this case evaluated data can be described by constant respectively linear MAC. Until 2015 MAC was decreasing for solar power while it was constant for wind power and biomass. However, the future course is uncertain. The "predicted" vanishing of abatement costs for solar power after an abatement of about 700 g/kWh is not plausible (see Fig. 8).

The vertical lines in Fig. 7 and 8 consider remaining emissions of the long-run objective. Since remaining emissions result in a left-shift of MAC_{ets} (see Section 2.1) internalized costs are respectively cut. The upper side of the lines corresponds to internalized costs if we face a long-run mitigation objective of 95 % when compared to emissions in 1990. The lower side means a long-run objective of 80 % reduction. These limits for remaining emissions reflect the long-run objectives of the EU (Council of the EU, 2009).

So far, we find internalized costs of the EU ETS above abatement costs of renewables ($C_{int} > C_r$, see Fig. 7b). The lowest common emission level of about 780 g/kWh was reached by renewables in 2002 and by the ETS in 2010. Up to that level Inequality 11 has held while a statement is impossible for lower emission levels. Thus, the promotion of renewable energy did not violate the minimum path up to that emission level.

However, abatements by renewable energy significantly exceed emission reductions by the EU ETS. When the ETS started in 2005 the advance of renewables was 50 g/kWh while it increased to about 250 g/kWh in 2015 (see Fig. 7). According to Working Group on Energy Balances (2018b), Federal Environment Agency (2018), Statistics of the Coal Sector (2018) this corresponds to ca. 31 – 38 % of 1990 emissions depending on whether 95 or 80 % of 1990 emissions shall be mitigated in the long run. This advance of renewables increases maximal additional costs in the worst-case scenario. Since we found linear MAC for the main components of renewables let us assume linear MAC for this analysis. Then for an advance of renewable energy amounting to 31 – 38 % of 1990 emissions relative additional costs increase from about 4 % to around 9 – 15 % (see Fig. 5). Since abatement effort must not be reduced to achieve the long-run objective for emission reduction, this result emphasizes the necessity to toughen up the EU ETS.

4 Conclusions

The promotion or renewable energy and emissions trading are overlapping regulations. On the one hand the simultaneous use of both policy instruments is advantageous. On the other hand the regulatory overlap may cause an efficiency loss in terms of additional costs. Excess costs arise if the promotion of renewable energy lasts too long and thus exceeds its optimal share to achieve the long-run objective. We develop a thumb rule to detect an excess of this optimal share. The rule indicates the regulator if it is necessary to modify the promotion policy. This restricts additional costs and thus increases the probability to obtain a positive net benefit from the promotion of RES.

Perfect implementation of the control mechanism restricts additional costs to about 4 % of total costs in a worst case scenario. The analysis turns out to be very robust. It holds for plausible pattern of marginal abatement costs (MAC) since any conical combination of weak convex power functions is included in the analysis. The mechanism is designed on an annual basis. Thus, it reacts on a change of MAC.

We further examine an imperfect implementation of the control mechanism knowing that perfect implementation of economic theory is rarely achievable. Perfect implementation in our case requires an equal emission reduction with promotion of renewable energy and emissions trading. Higher abatements by renewables when compared to the ETS potentially increase possible maximum additional costs. Excess costs also depend on the shape of MAC in this case. Nevertheless additional costs stay rather small under a slightly imperfect implementation of the control mechanism.

Applying our model to the German electricity sector we find no violation of the path of minimum costs by promotion of RES so far. However, data are very limited because the EU ETS has not achieved any additional emission reduction since 2010. In comparison to the emission reduction induced by the ETS we find an advance of renewables amounting to about 31 – 38 % of 1990 emissions depending on whether 95 or 80 % of 1990 emissions shall be mitigated in the long run. Thus, in Germany additional costs are restricted to about 9 – 15 % of total costs instead of 4 % in a worst case scenario. This result emphasizes the necessity to toughen up the EU ETS.

The introduction of the thumb rule is a promising approach to coordinate promotion of RES and an ETS. However, further refinements of the analysis allowing more results than a worst case scenario would be a benefit. Moreover, the necessary empirical assessment seeks for further research.

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A Worst-case analysis of additional abatement costs

Overlapping regulations like the promotion of RES and the ETS may cause additional abatement costs. Additional costs depend on the course of marginal abatement cost linked to the ETS (MAC_{ets}) and the promotion of renewable energy (MAC_r). In Appendix A.1 we analyze maximal additional costs under the assumption of linear MAC. In Appendix A.2 we generalize our findings to weak convex power functions which proves to be valid for any conical combination of weak convex power functions, too (see Appendix A.3).

A.1 Linear MAC

Linear MAC are represented by

$$MAC_r = -d_r E + b_r \tag{30}$$

$$MAC_{ets} = -d_{ets} E + b_{ets} \tag{31}$$

with $b_{ets} = d_{ets} E^{''}$. The negative signs in Eq. 30, 31 indicate increasing MAC with respect to emission abatement. This implies decreasing MAC with respect to emissions so that d_r and d_{ets} themselves are both positive for increasing MAC while they are both negative for decreasing MAC.

The inversion of increase and decrease of emissions with respect to the abscissa of MAC_r, according to the modified representation of Fig. 3, yields

$$MAC_r^{'} = d_r E + b_r^{'} \tag{32}$$

with

$$b_r^{'} := b_r - d_r E_t. \tag{33}$$

A possible long-run residual of emissions can be considered by a respective shifting of MAC_{ets} (see Section 2.2). If a share σ of initial emissions $E^{''}$ remains in the long-run this will mean a reduction of the intercept by the same share leading to

$$MAC_{ets}^{'} = -d_{ets} E + b_{ets}^{'} \tag{34}$$

with

$$
\begin{aligned}
b'_{ets} &= b_{ets}(1-\sigma) \\
&= d_{ets}E''(1-\sigma) \\
&:= d_{ets}\tilde{E}''.
\end{aligned} \tag{35}
$$

$\tilde{E}''$ reflects effective emissions which have to be totally mitigated to achieve the long-run objective of emission reduction. The emission level of the turning point of mitigation strategies E_t is determined by the intersection of MAC curves. Using Eq. 32 and 34 we obtain

$$
E_t = \frac{b'_{ets} - b'_r}{d_r + d_{ets}}. \tag{36}
$$

Eq. 36 is only a theoretical construction to get results for the reference case because the exact course of MAC curves is not known in reality.

The axis intercepts of MAC (b'_r, b'_{ets}) reflect initial MAC_r for abatements with renewables and final MAC_{ets} for abatement induced by the ETS. Therefore b'_r and b'_{ets} are restricted to positive values. In addition, we reasonably assume the necessity of renewable energy to achieve the long-run objective (see Section 1) yielding the plausible assumption

$$
b'_{ets} \geq b'_r \geq 0 \tag{37}
$$

whereas the equal signs correspond to the respective limiting case.

Although the course of MAC is not known in reality the emission level of the turning point can be approximated by equalizing costs C_{int}, which are already internalized by the ETS, and abatement costs of renewable energy C_r (see Section 2.1). This yields

$$
\tilde{E}_t = \frac{b'_{ets} - b'_r}{\frac{1}{2}d_r + d_{ets}}. \tag{38}
$$

$d_r = 0$ results in $E_t = \tilde{E}_t$ while increasing MAC ($d_r > 0$, $d_{ets} > 0$) yields $\tilde{E}_t > E_t$, so that the approximated turning point $\tilde{E}_t$ causes additional abatement costs

$$
\begin{aligned}
\Delta C &= \int_{E_t}^{\tilde{E}_t} \Big(MAC'_r(E) - MAC'_{ets}(E) \Big)\,\mathrm{d}E \\
&= \frac{d_r^2 (b'_{ets} - b'_r)^2}{8\left(\frac{1}{2}d_r + d_{ets}\right)^2 (d_r + d_{ets})}
\end{aligned} \tag{39}
$$

when compared to the reference case (triangle in Fig. 3).

Total abatement costs consist of abatement costs C_{ets} which are induced by the ETS and abatement costs C_r which are caused by the substitution of fossil by renewable energy sources. This yields

$$
\begin{aligned}
C &= C_r + C_{ets} \\
&= \int_0^{\tilde{E}_t} MAC_r^{'}(E)\mathrm{d}E + \int_{\tilde{E}_t}^{\tilde{E}''} MAC_{ets}^{'}(E)\mathrm{d}E \\
&= \frac{\tilde{E}'' + \tilde{E}_t}{2\tilde{E}_t} C_r
\end{aligned}
\tag{40}
$$

with

$$
C_r = \frac{\left(\frac{1}{2}d_r b_{ets}^{'} + d_{ets} b_r^{'}\right)\left(b_{ets}^{'} - b_r^{'}\right)}{\left(\frac{1}{2}d_r + d_{ets}\right)^2}. \tag{41}
$$

This leads to

$$
C = \frac{-d_{ets}^2 b_r^{'2} + \frac{1}{4}d_r^2 b_{ets}^{'2} + d_r d_{ets} b_{ets}^{'2} + 2d_{ets}^2 b_r^{'} b_{ets}^{'}}{2d_{ets}\left(\frac{1}{2}d_r + d_{ets}\right)^2} \tag{42}
$$

which includes additional costs ΔC as $\tilde{E}_t$ instead of E_t is taken into account in Eq. 40.

Defining $\delta := \frac{d_r}{d_{ets}}$ and $\beta := \frac{b_r^{'}}{b_{ets}^{'}}$ additional abatement costs can be expressed as share of total costs

$$
\begin{aligned}
\Delta C_{rel} &= \frac{\Delta C}{C} \\
&= \frac{\delta^2(1-\beta)^2}{4(\delta+1)(\frac{1}{4}\delta^2 - \beta^2 + \delta + 2\beta)}
\end{aligned}
\tag{43}
$$

which defines relative additional costs. As expected ΔC_{rel} equals zero for $d_r = \delta = 0$.

To set up a worst-case scenario with respect to relative additional costs we maximize Eq. 43 with respect to β resulting in

$$
\begin{aligned}
\frac{\partial \Delta C_{rel}}{\partial \beta} &= -\frac{\delta^2(\frac{1}{4}\delta^2 + \delta + 1)}{2(1+\delta)} \frac{(1-\beta)}{2(\frac{1}{4}\delta^2 + \delta + \beta(2-\beta))^2} \\
&\leq 0.
\end{aligned}
\tag{44}
$$

This indicates an extremum for $\beta = 1$ which is a minimum because ΔC_{rel} equals zero in this case (see Eq. 43). Since δ is restricted to positive values for increasing MAC ($d_r > 0$, $d_{ets} > 0$) and β is, according to Inequality 37 lower than or equal to one, Eq. 44 is, except for $\beta = 1$, always negative. Thus, ΔC_{rel} increases for decreasing β. However, β is restricted to a minimum of zero (see Inequality 37). Therefore relative additional costs are at their maximum for the corner solution $\beta = 0$.

The derivative of ΔC_{rel} with respect to δ yields

$$\frac{\partial \Delta C_{rel}}{\partial \delta} = \frac{(1-\beta)^2}{4} \frac{\left(\frac{1}{2}\delta + 1\right)\left(\delta - 2\beta^2 + 4\beta - \frac{1}{2}\delta^2\right)\delta}{(\delta+1)^2(\frac{1}{4}\delta(\delta+1) - \beta^2 + 2\beta)^2} \tag{45}$$

leading to four possible extrema

$$\delta = -2 \vee \delta = 0 \vee \delta = 1 \pm \sqrt{1 + 4\beta(2-\beta)}. \tag{46}$$

If we take into account the maximum condition $\beta = 0$ and consider $\delta > 0$ for increasing MAC we find the only possible maximum for $\delta = 2$ because ΔC_{rel} is zero for $\delta = 0$ (see Eq. 43). This finding is confirmed if we evaluate Eq. 45 for values around the possible maximum. Since $\frac{\partial \Delta C_{rel}}{\partial \delta}$ is always positive for $0 \leq \beta \leq 1$ and δ in the interval between zero and two while we receive negative values for δ exceeding two relative additional costs reach their maximum for $\delta = 2$.

Inserting the maximizing values for δ and β in Eq. 43 leads to

$$\max_{\beta,\delta} \Delta C_{rel} = \frac{1}{9} \qquad \forall \beta \geq 0 \wedge \delta \geq 0 \tag{47}$$

as maximum.

Since $\delta = 2$ clearly violates Eq. 2 and ΔC_{rel} increases with δ in the relevant interval between zero and two we obtain for the resulting corner solution $\delta = 1$

$$\max_{\beta,\delta} \Delta C_{rel} = \frac{1}{10} \qquad \forall \beta \geq 0 \wedge 0 \leq \delta \leq 1. \tag{48}$$

A.1.1 Introduction of a necessary constraint

The analysis so far does not take into account that, under perfect implementation of our control mechanism, $\tilde{E}_t$ is restricted to $\frac{\tilde{E}''}{2}$ at its maximum (see Section 2.2 for a more detailed explanation). Additional costs can only occur if E_t is lower than $\frac{\tilde{E}''}{2}$. However, E_t exactly equals $\frac{\tilde{E}''}{2}$ for the maximum conditions derived above ($\beta = 0$, $\delta = 1$). That is substitution of fossil-based power plants contributes exactly half of total emission reduction. As a consequence additional costs can only occur for $\beta > 0$ under perfect implementation of the control mechanism leading to $\tilde{E}_t \leq \frac{\tilde{E}''}{2}$.[9]

Starting from $\beta = 0$ an increase of β will at first only decrease E_t because $\tilde{E}_t$ is still restricted to $\frac{\tilde{E}''}{2}$. This results in a disproportional higher increase of ΔC when com-

[9] Additional costs could also occur for $\delta > 1$. However, according to Section 2, this would be implausible (see Eq. 2) and is thus excluded from the analysis.

pared to C eventually resulting in an increase of relative additional costs (see Section A.2.1 for proof). This behavior stops as soon as $\tilde{E}_t < \frac{\tilde{E}''}{2}$ because the restriction $\tilde{E}_t = \frac{\tilde{E}''}{2}$ is not binding anymore. Then, according to Inequality 44, lower values for β lead to higher relative additional costs. That makes β decrease until the restriction $\tilde{E}_t = \frac{\tilde{E}''}{2}$ is binding again. Thus, for perfect implementation of the control mechanism relative additional cost must reach their maximum if this restriction is just binding. Substitution of $\tilde{E}_t$ by $\frac{\tilde{E}''}{2}$ in Eq. 38 and rearrangement with respect to $b_r^{'}$ yields

$$\begin{aligned} b_r^{'} &= \left(d_{ets} - \frac{d_r}{2}\right)\frac{\tilde{E}''}{2} \\ \Rightarrow \beta &= \frac{2-\delta}{4}. \end{aligned} \tag{49}$$

The second line in Eq. 49 considers Eq. 35.

Since ΔC_{rel} is maximized for $\delta = 1$ we get $\beta = 0.25$ as maximum condition finally leading to

$$\max_{\beta,\delta} \Delta C_{rel} = \frac{1}{24} \qquad \forall 0 \leq \beta \leq \frac{2-\delta}{4} \wedge 0 \leq \delta \leq 1. \tag{50}$$

This corresponds to the maximum of relative additional costs under perfect implementation of the control mechanism.

Perfect implementation of the control mechanism assumes always to have identical emission reduction induced by the ETS and the promotion of RES. Non-identical but higher reduction by RES increases the risk of higher additional costs. Let us assume emission reduction with RES exceeds emission reduction induced by the ETS for instance by $x\tilde{E}''$. Then $\tilde{E}$ is restricted to $\frac{\tilde{E}''}{2}(1+x)$ instead of $\frac{\tilde{E}''}{2}$ (see Section 2.2 for a more detailed explanation). In this case the constraint given in Eq. 49 turns into a more general form

$$\begin{aligned} b_r^{'} &= \left(d_{ets} - \frac{d_r}{2}\right)\frac{\tilde{E}''}{2} - \left(\frac{d_r}{2} + d_{ets}\right)\frac{\tilde{E}''}{2}x \\ \Rightarrow \beta &= \frac{2-\delta}{4} - \frac{2+\delta}{4}x. \end{aligned} \tag{51}$$

According to Inequality 37, β is restricted to positive values. β decreases for increasing x and becomes zero for $x = \frac{2-\delta}{2+\delta}$. Under the maximum condition δ equals one β is positive for $x \leq 1/3$ while β is equal to zero for higher x. Higher values for x lead to a massive increase of relative additional costs (see Fig. 5 in Chapter 2.2).

A.2 MAC approximated by weak convex power functions

To generalize findings from Appendix A.1 we define, in analogy to Eq. 30 and 34, MAC as power functions

$$
\begin{aligned}
MAC'_{r,i}(E) &= d_{r,i}E^i + b'_{r,i} \\
MAC'_{ets,i}(E) &= d_{ets,i}(\tilde{E}'' - E)^i
\end{aligned} \tag{52}
$$

with $b'_{ets,i} = d_{ets,i}\tilde{E}''^i$. The turning point E_t, as theoretical reference case, is still determined by the intersection of MAC curves

$$
MAC'_{r,i}(E_t) - MAC'_{ets,i}(E_t) = 0 \tag{53}
$$

while the approximated turning point $\tilde{E}_t$, according to Eq. 12, fulfills

$$
\int_0^{\tilde{E}_t} MAC'_{r,i}(E)\mathrm{d}E - MAC'_{ets,i}(\tilde{E}'' - \tilde{E}_t) \cdot (\tilde{E}'' - \tilde{E}_t) = 0. \tag{54}
$$

Using the approximated instead of the real turning point leads to

$$
\Delta C = \int_{E_t}^{\tilde{E}_t} \Big(MAC'_{r,i}(E) - MAC'_{ets,i}(E) \Big) \,\mathrm{d}E \tag{55}
$$

as additional costs. Abatement costs consist of costs C_r which are induced by subsidizing renewables and costs C_{ets} stemming from the ETS

$$
\begin{aligned}
C &= C_r + C_{ets} \\
&= \int_0^{\tilde{E}_t} MAC'_{r,i}(E)\mathrm{d}E + \int_{\tilde{E}_t}^{\tilde{E}''} MAC'_{ets,i}(E)\mathrm{d}E.
\end{aligned} \tag{56}
$$

Requested relative additional costs are given by

$$
\Delta C_{rel} = \frac{\Delta C}{C}. \tag{57}
$$

Convex MAC require a refinement of Inequality 37 which reflects the relation between b'_r as initial MAC$_r$ and b'_{ets} as final MAC$_{ets}$. High initial marginal abatement cots for renewables b'_r can lead to a situation in which abatement costs of RES $C_r(E')$ are initially or even permanently higher than internalized costs of the ETS $C_{int}(\tilde{E}'' - E')$ although Inequality 37 is still fulfilled. Thus, we redefine Inequality 37 resulting in

$$
b'_{ets,i} \geq b_{max,i} \geq b'_{r,i} \geq 0 \tag{58}
$$

with $b_{max,i}$ defining the maximal value for $b'_{r,i}$ which still allows a solution of Eq. 54 (see Section 2.3 for details). For $i = 1$ and $i = 2$ analytical solutions are available while other exponents require a numerical solution. While the solution for $i = 1$ is given by Inequality 37, $i = 2$ yields $b_{max,2} = \frac{3}{4(3+\delta_2)} b'_{ets,2} = \frac{3}{4(3+\delta_2)} d_{ets,2} \left(\frac{\tilde{E}''}{2}\right)^2$ using $\delta_i := d_{r,i}/d_{ets,i}$.

Considering Inequality 58 numerical calculations prove that ΔC_{rel} is maximized for the corner solution $b'_{r,i} = 0$ ($\beta_i = 0$) for all weak convex power functions ($i \geq 1$) respectively for any monomial ($i \in \mathbb{N}$) (see Fig. 9 for results). That is $\partial \Delta C_{rel} / \partial b_{\tilde{i},r} < 0 \; \forall \; b_{max,i} \geq b'_{r,i} \geq 0$.

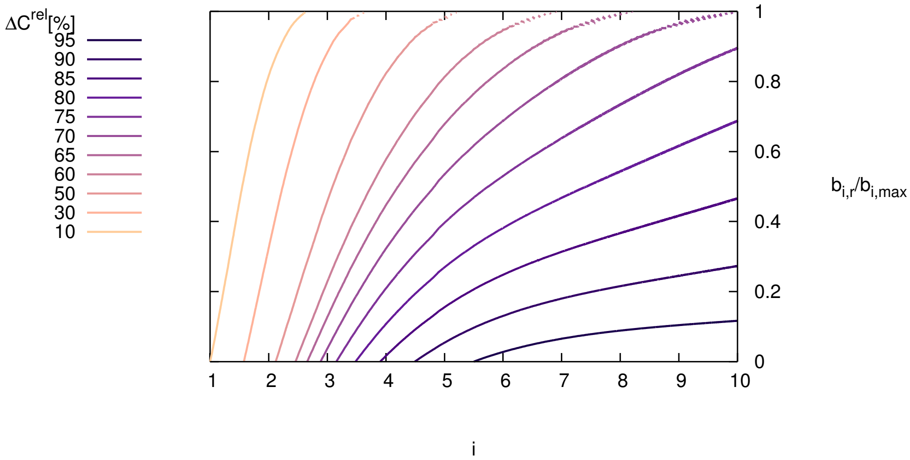

Figure 9: Evolution of relative additional costs ΔC_{rel} for weak convex power functions with $1 \leq i \leq 10$. We chose δ_i to maximize ΔC_{rel}. Both E_t and $\tilde{E}_t$ are calculated numerically. The interrupted lines near $b'_{r,i}/b_{max,i} = 1$ are due to the wide range of $b_{max,i}$ and the resulting projection of the graph. For any i ΔC_{rel} is maximized for $b'_{r,i} = 0$.

For concave functions with a certain degree of concavity the properties of ΔC_{rel} with respect to $b'_{r,i}$ are inverted. For $i \lesssim 0.82$ we find the maximum of ΔC_{rel} for increasing instead of decreasing $b_{r,i}$. This leads to the corner solution $b'_{r,i} = b_{max,i}$ because $b'_{r,i}$ is restricted to $b_{max,i}$ at its maximum (see Inequality 58). However, physical limitations of emissions abatement in the fossil sector give reason for a convex shape of MAC_{ets} while concave MAC are not realistic. With respect to renewable energy the probability for concave MAC might be higher although a higher share of RES-based power plants might lead to a disproportional higher increase of costs caused by intermittent electricity generation. Nevertheless, this does not affect our worst case scenario which aims at a maximization of relative additional costs because concave MAC_r would decrease estimated additional relative costs. Therefore we can exclude them from our analysis without the loss of generality.

A.2.1 Maximization with respect to initial costs $b'_{r,i}$

In Sections A.1 we analyzed the behavior of β respectively b'_r to maximize ΔC_{rel} for linear MAC. There are two different behavioral patterns depending on whether the restriction $\tilde{E}_t = \frac{\tilde{E}''}{2}$ is binding or not. If this restriction is not binding decreasing β (b'_r) maximizes relative additional costs leading to the corner solution $b'_r = \beta = 0$ (see Eq. 44). So far we know from numerical calculations that this behavior also applies for any weak convex power function (see Fig. 6). We still need to find out the behavior of $b'_{r,i}$ if the restriction $\tilde{E}_t = \frac{\tilde{E}''}{2}$ is binding. That is $\tilde{E}_t$ is constant which leads to $\frac{\mathrm{d}\tilde{E}'_t}{\mathrm{d}b_{r,i}} = 0$. Consideration of Eq. 56 and 55 yields for constant $\tilde{E}_t$

$$\begin{aligned}\frac{\mathrm{d}\Delta C}{\mathrm{d}b'_{r,i}} &= \frac{\tilde{E}''}{2} - E_t - \underbrace{\left(b'_{r,i} + d_{r,i}E_t^i - d_{ets,i}(\tilde{E}'' - E_t)^i\right)}_{MAC'_{r,i}(E_t) - MAC'_{ets,i}(E_t) = 0}\frac{\mathrm{d}E_t}{\mathrm{d}b'_{r,i}} \\ &= \frac{\tilde{E}''}{2} - E_t > 0\end{aligned} \tag{59}$$

and

$$\frac{\mathrm{d}C}{\mathrm{d}b'_{r,i}} = \frac{\tilde{E}''}{2} > 0. \tag{60}$$

We define the elasticities

$$\begin{aligned}\epsilon_{\Delta C} &:= \frac{\mathrm{d}\Delta C}{\mathrm{d}b'_{r,i}}\frac{b'_{r,i}}{\Delta C} \\ \epsilon_C &:= \frac{\mathrm{d}C}{\mathrm{d}b'_{r,i}}\frac{b'_{r,i}}{C}\end{aligned} \tag{61}$$

and state Lemma 1:

$$\epsilon_{\Delta C} > \epsilon_C \qquad \forall \tilde{E}_t = \text{const.} \tag{62}$$

Considering $\Delta C = C - \int_0^{E_t} MAC'_{r,i}(E)\mathrm{d}E - \int_{E_t}^{\tilde{E}''} MAC'_{ets,i}(E)\mathrm{d}E$ (see Eq. 55, 56) this yields

$$\begin{aligned}&\frac{\left(\frac{\tilde{E}''}{2} - E_t\right)b'_{r,i}}{C - \left(b_{r,i}E_t + \frac{d_{r,i}}{i+1}E_t^{i+1} + \frac{d_{ets,i}}{i+1}(\tilde{E}'' - E_t)^{i+1}\right)} > \frac{\frac{\tilde{E}''}{2}b'_{r,i}}{C} \\ \Leftrightarrow\ &\frac{1}{E_t}\left((\tilde{E}'' - E_t)^{i+1} + E_t^{i+1}\delta_i\right) > \left(\frac{\tilde{E}''}{2}\right)^i + \left(\frac{\tilde{E}''}{2}\right)^i\delta_i.\end{aligned} \tag{63}$$

Recalling that relative additional costs only occur if the real turning point E_t is lower than $\frac{\tilde{E}''_t}{2}$ (see Section A.1.1) the last line in Eq. 63 is clearly fulfilled for weak convex functions ($i \geq 1$) with $\delta \leq 1$. This proves Lemma 1. The result becomes obvious if we assume for a moment $\frac{\tilde{E}_t''}{2} = E_t$ which makes Inequality 63 merge into equality.

The proof of Lemma 1 implies that for constant $\tilde{E}_t$, an increasing $b_{r,i}^{'}$ results in a higher relative increase of ΔC when compared to C. This means increasing ΔC_{rel} for increasing $b_{r,i}^{'}$ in this case while the opposite is true for non-constant $\tilde{E}_t$ as we know from numerical calculations (see Appendix A.2). The result is a maximum for ΔC_{rel} if $\tilde{E}_t$ equals $\frac{\tilde{E}''}{2}$. As discussed in Section A.1.1 imperfect implementation of the control mechanism might increase $\tilde{E}_t$ to $\frac{\tilde{E}''}{2}(1+x)$. If we substitute $\tilde{E}_t$ by $\frac{\tilde{E}''}{2}(1+x)$ in Eq. 54 we receive

$$\begin{aligned} b_{r,i}^{'} &= \left(\frac{1-x}{1+x} d_{ets,i} - \frac{d_{r,i}}{1+i}\right)\left(\frac{\tilde{E}''}{2}\right)^i (1+x)^i \\ \Rightarrow \beta_i &= \left(\frac{1-x}{1+x} - \frac{\delta_i}{1+i}\right)\left(\frac{1+x}{2}\right)^i \end{aligned} \tag{64}$$

with $\beta_i := b_{r,i}^{'}/b_{ets,i}^{'}$. Eq. 64 turns into to Eq. 51 for $i = 1$.

A.3 MAC approximated by a conical combination of weak convex power functions

In the next step of our analysis we apply our findings to a conical combination ($d_{ets,i} \geq d_{r,i} \geq 0$) of weak convex power functions

$$\begin{aligned} MAC_r^{'}(E) &= \sum_{i \geq 1}^{n} MAC_{r,i}^{'}(E) \\ &= \sum_{i \geq 1}^{n} \left(d_{r,i} E^i + b_{r,i}^{'}\right) \\ MAC_{ets}^{'}(E) &= \sum_{i \geq 1}^{n} MAC_{ets,i}^{'}(E) \\ &= \sum_{i \geq 1}^{n} d_{ets,i} (\tilde{E}'' - E)^i. \end{aligned} \tag{65}$$

We define $b_r^{'} := \sum_{i \geq 1}^{n} b_{r,i}^{'}$ as initial costs for RES.

A.3.1 Maximization with respect to initial costs $b'_{r,i}$

To evaluate the behavior of ΔC_{rel} with respect to initial costs b'_r we can analyze Lemma 1 (see Inequality 62) for a conical combination of power plants which yields

$$\frac{1}{E_t}\sum_{i\geq 1}^{n}\frac{1}{1+i}\left((\tilde{E}''-E_t)^{i+1}+E_t^{i+1}\delta_i\right)\overset{?}{\gtrless}\frac{1}{\tilde{E}_t}\sum_{i\geq 1}^{n}\frac{1}{1+i}\left((\tilde{E}''-\tilde{E}_t)^{i+1}+\tilde{E}_t^{i+1}\delta_i\right)$$
$$-\sum_{i\geq 1}^{n}\frac{MAC'_{r,i}(\tilde{E}_t)-MAC'_{ets,i}(\tilde{E}_t)}{E_t\tilde{E}_t}\sum_{i\geq 1}^{n}\left(\frac{1}{1+i}(\tilde{E}''-\tilde{E}_t)^{i+1}+\frac{\delta_i}{1+i}\tilde{E}_t^{i+1}+\frac{b'_{r,i}}{d_{ets,i}}\right)\frac{\partial\tilde{E}_t}{\partial b'_r}. \tag{66}$$

Let us at first assume that the restriction $\tilde{E}_t=\frac{\tilde{E}''}{2}$ is binding (constant $\tilde{E}_t$). This has two effects. First, $\frac{\partial\tilde{E}_t}{\partial b'_r}$ equals zero so that the second line of Inequality 66 vanishes. Second, we can replace $\tilde{E}_t$ by $\frac{\tilde{E}''}{2}$ in Inequality 66. Then Inequality 66 consists of a sum of the last line of Inequality 63 over all i. That is Inequality 63 corresponds to the summands of Inequality 66.

Since each summand fulfills Lemma 1 (see Inequality 63), it is also fulfilled for the sum. Thus, the left hand side of Inequality 66 is larger than the right hand side for constant $\tilde{E}_t$. This proves that an increasing $b'_{r,i}$ results in a higher relative increase of ΔC when compared to C. Thus, ΔC_{rel} is maximized for increasing b'_r as long as $\tilde{E}_t$ is constant. The result holds for any weak convex power function and any conical combination of weak convex power functions.

In contrast to this result we found for any weak convex power function that ΔC_{rel} is maximized for b'_r equals zero if $\tilde{E}_t$ is not constant (see Fig. 9). In the following we analyze which effects lead to this result. This allows to draw conclusions for a conical combination of power functions.

Increasing initial costs b'_r ceterum paribus always lead to higher total costs C (see Fig. 3 for illustration). On the one hand this leads to increasing relative additional costs ΔC_{rel} if the relative increase of C is lower than the relative increase of additional costs ΔC. That is Lemma 1 (Inequality 62) is fulfilled. On the other hand this leads to decreasing relative additional costs ΔC_{rel} if the relative increase of additional costs ΔC is lower (or we even find decreasing ΔC) than the relative increase of total costs C. That means the reversion of Lemma 1 leading to Lemma 1b:

$$\epsilon_{\Delta C}<\epsilon_C \qquad \forall\tilde{E}_t\neq\text{const.} \tag{67}$$

Inequality 67 is a necessary and sufficient condition for the result of our numerical calculations after which ΔC_{rel} is maximized for b'_r equals zero if $\tilde{E}_t$ is not constant (see Fig. 9).

Thus, according to our numerical calculations

$$\begin{aligned}&\frac{1}{E_t}\cdot\frac{1}{1+i}\left((\tilde{E}''-E_t)^{i+1}+E_t^{i+1}\delta_i\right)<\frac{1}{\tilde{E}_t}\cdot\frac{1}{1+i}\left((\tilde{E}''-\tilde{E}_t)^{i+1}+\tilde{E}_t^{i+1}\delta_i\right)\\&-\underbrace{\frac{MAC_r'(\tilde{E}_t)-MAC_{ets}'(\tilde{E}_t)}{E_t\tilde{E}_t}}_{>0}\underbrace{\left(\frac{1}{1+i}(\tilde{E}''-\tilde{E}_t)^{i+1}+\frac{\delta_i}{1+i}\tilde{E}_t^{i+1}+\frac{b_{r,i}'}{d_{ets,i}}\right)}_{>0}\frac{\partial\tilde{E}_t}{\partial b_r'}\end{aligned}\tag{68}$$

holds for any weak convex power function. The first line in Inequality 68 corresponds to Inequality 63 with reversed proportions. Therefore the second line of Inequality 68 must be the reason for the inversion of proportions. The fraction in the second line is always positive because the real turning point E_t is always lower than the estimated turning point $\tilde{E}_t$ (see Section 2.2). This leads to $MAC_r'(\tilde{E}_t) > MAC_{ets}'(\tilde{E}_t)$ (see Fig. 3 in Chapter 2.2). The term in brackets is positive because it exclusively consists of positive summands. Increasing b_r' shifts the function upwards (see Fig. 3 for illustration). This decreases $\tilde{E}_t$. Thus, the derivative $\frac{\partial\tilde{E}_t}{\partial b_r'}$ is always negative. This gives the whole second line of Inequality 68 a positive sign which makes the right hand side of Inequality 68 larger than the left hand side. This leads to reversed proportions when compared to Inequality 63.

A comparison of Inequality 68 and Inequality 66 allows to draw conclusions for conical combinations of weak convex power functions. Inequality 68 is a summand of Inequality 66, whereby Inequality 66 faces additional terms because its second line is a product of two sums. Since all summands of these sums are positive their product yields n times n positive terms. Thus, we can rewrite Inequality 66 as

$$\begin{aligned}&\frac{1}{E_t}\sum_{i\geq1}^{n}\frac{1}{1+i}\left((\tilde{E}''-E_t)^{i+1}+E_t^{i+1}\delta_i\right)\overset{?}{\gtrless}\frac{1}{\tilde{E}_t}\sum_{i\geq1}^{n}\frac{1}{1+i}\left((\tilde{E}''-\tilde{E}_t)^{i+1}+\tilde{E}_t^{i+1}\delta_i\right)\\&-\sum_{i\geq1}^{n}\frac{MAC_{r,i}'(\tilde{E}_t)-MAC_{ets,i}'(\tilde{E}_t)}{E_t\tilde{E}_t}\left(\frac{1}{1+i}(\tilde{E}''-\tilde{E}_t)^{i+1}+\frac{\delta_i}{1+i}\tilde{E}_t^{i+1}+\frac{b_{r,i}'}{d_{ets,i}}\right)\frac{\partial\tilde{E}_t}{\partial b_r'}\\&-\underbrace{R}_{>0}\frac{\partial\tilde{E}_t}{\partial b_r'}\end{aligned}\tag{69}$$

with R containing all remaining $n-1$ times n positive terms. These additional terms, which appear in a conical combination of power functions, increase the right hand side of Inequality 69 even more. Therefore Lemma 1b is fulfilled for any conical combination of weak convex power functions as long as every weak convex power function of the conical combination fulfills Lemma 1b (Inequality 67). Our numerical calculations for weak convex power functions with respect to b_r' thus also apply for any conical combination of weak convex power functions. Consequently ΔC_{rel} is also maximized for any conical combination of weak convex power functions if the restriction $\tilde{E}_t = \frac{\tilde{E}''}{2}$ is binding. Considering Eq. 64 this yields for imperfect implementation of the control mechanism

$$\begin{aligned} b_r^{'} &:= \sum_{i\geq 1}^{n} b_{r,i}^{'} \\ &= \sum_{i\geq 1}^{n} \left(\frac{1-x}{1+x} d_{ets,i} - \frac{d_{r,i}}{1+i} \right) \left(\frac{\tilde{E}''}{2} \right)^i (1+x)^i. \end{aligned} \tag{70}$$

A.3.2 Maximization with respect to the ratio of coefficients δ_i

Assuming perfect implementation of the control mechanism ($x = 0$) for simplicity with respect to the following calculations we can replace $b_r^{'} := \sum_{i\geq 1}^{n} b_{r,i}^{'}$ in Eq. 65 by Eq. 70 which considers the restriction $\tilde{E}_t = \frac{\tilde{E}''}{2}$

$$\begin{aligned} MAC_r(E) &= \sum_{i\geq 1}^{n} \left[d_{r,i} E^i + \left(d_{ets,i} - \frac{d_{r,i}}{i+1} \right) \left(\frac{\tilde{E}''}{2} \right)^i \right] \\ MAC_{ets}(E) &= \sum_{i\geq 1}^{n} d_{ets,i} (\tilde{E}'' - E)^i \end{aligned} \tag{71}$$

Inserting Eq. (71) into Eq. (57) yields with $\delta_i := \frac{d_{r,i}}{d_{ets,i}}$.

$$\Delta C_{rel} = 1 - \frac{\sum_{i\geq 1}^{n} d_{ets,i} \left[\left(1 - \frac{\delta_i}{i+1}\right) \left(\frac{\tilde{E}''}{2}\right)^i E_t + \frac{\delta_i}{i+1} E_t^{i+1} + \frac{1}{i+1} (\tilde{E}'' - E_t)^{i+1} \right]}{\sum_{i\geq 1}^{n} d_{ets,i} \left[\left(1 - \frac{\delta_i}{i+1}\right) \left(\frac{\tilde{E}''}{2}\right)^{i+1} + \frac{\delta_i}{i+1} \left(\frac{\tilde{E}''}{2}\right)^{i+1} + \frac{1}{i+1} \left(\frac{\tilde{E}''}{2}\right)^{i+1} \right]}. \tag{72}$$

To find out the behavior of the function with respect to δ_i we take the respective derivative

$$\begin{aligned} \frac{\mathrm{d}\Delta C_{rel}}{\mathrm{d}\delta_i} &= \frac{\frac{d_{ets,i}}{i+1} E_t \left[\left(\frac{\tilde{E}''}{2}\right)^i - E_t^i \right]}{\sum_{i\geq 1}^{n} d_{ets,i} \left[\left(1 - \frac{\delta_i}{i+1}\right) \left(\frac{\tilde{E}''}{2}\right)^{i+1} + \frac{\delta_i}{i+1} \left(\frac{\tilde{E}''}{2}\right)^{i+1} + \frac{1}{i+1} \left(\frac{\tilde{E}''}{2}\right)^{i+1} \right]} \\ &> 0. \end{aligned} \tag{73}$$

Eq. 73 is always positive because $\tilde{E}_t = \frac{\tilde{E}''}{2} > E_t$ and δ_i is limited to values lower or equal to one while i is larger than or equal to one. Therefore an increase in δ_i results in higher relative additional costs leading to the corner solution $\delta_i = 1$. Thus, it is sufficient to restrict the worst-case analysis to $d_{r,i} = d_{ets,i} := d_i$ in the following.

A.3.3 Reduction to single power functions

Relative additional costs are at their maximum if the fraction in Eq. 72 is minimized. The fraction consists of all power functions which are part of a certain conical combination. For further analysis we at first look at each power plant separately, the conical combination consists of. There will be one power function with $i = l$ yielding highest relative additional costs if Eq. 72 is evaluated for this power function only instead of the conical combination as a whole. In the following we want to prove that this power function $i = l$ leads to higher relative additional costs than the conical combination it is part of as a whole. If this lemma is proved our worst-case analysis can be deduced to single weak convex power functions so that all results hold for conical combinations as well.

We state Lemma 2:

$$\begin{aligned} &\frac{\sum_{i\geq 1}^{n} d_{ets,i}\left[\frac{i}{i+1}\left(\frac{\tilde{E}''}{2}\right)^{i} E_t + \frac{1}{i+1}E_t^{i+1} + \frac{1}{i+1}(\tilde{E}'' - E_t)^{i+1}\right]}{\sum_{i\geq 1}^{n} d_{ets,i}\frac{i+2}{i+1}\left(\frac{\tilde{E}''}{2}\right)^{i+1}} \\ &> \frac{d_{l,ets}\left[\frac{l}{l+1}\left(\frac{\tilde{E}''}{2}\right)^{l} E_t + \frac{1}{l+1}E_t^{l+1} + \frac{1}{l+1}(\tilde{E}'' - E_t)^{l+1}\right]}{d_{l,ets}\frac{l+2}{l+1}\left(\frac{\tilde{E}''}{2}\right)^{l+1}} \end{aligned} \tag{74}$$

Lemma 2 uses Eq. 72 with $\delta_i = 1$ to compare relative additional costs of a conical combination of power functions (first line of Inequality 74) with relative additional costs of the power function $i = l$ which is part of the conical combination (second line of Inequality 74).

Counter and denominator of the second line of Inequality 74 are summands in the first line. Thus, a conical combination of power functions results in a separate summation over all n power function for both counter and denominator. This is in analogy to the summation of two-dimensional vectors.[10] Therefore Lemma 2 is true if we assume, in a first step, that E_t never changes whether we consider a conical combination or a single power function.

However, this is a strong assumption. Different power functions may of course have different turning points E_t. A conical combination of such functions will thus change E_t when compared to the power function separately. Let us assume for example the

[10] The summation of two-dimensional vectors with different slopes result in a vector which has a lower/higher slope than the highest/lowest slope of the vectors which were summed up. The slope is the ratio of the two compounds of the vector which corresponds to counter and denominator in Eq. 72.

function $i = l$ is combined with a function $i = \tilde{i}$. If E_t of function $i = \tilde{i}$ is larger than E_t of function $i = l$ a conical combination of the two power functions will increase E_t when compared to the power function $i = l$. In this case the derivative $\frac{\partial E_t}{\partial d_{\tilde{i}}}$ is positive. If E_t of function $i = \tilde{i}$ is lower than E_t of function $i = l$ a conical combination of the two power functions will result in a negative derivative $\frac{\partial E_t}{\partial d_{\tilde{i}}}$.

Under these conditions Lemma 2 only holds if a change of E_t induced by consideration of further power functions never leads to an increase of relative additional costs of the decisive power function $i = l$. That is we need to prove that the derivative of relative additional costs of power function $i = l$ with respect to any coefficient $d_{\tilde{i}}$ is never positive. The relevant derivative yields

$$\frac{\partial \Delta C_{rel}}{\partial d_{\tilde{i}}} = -\frac{l+1}{l+2}\left(\frac{\tilde{E}''}{2}\right)^{-(l+1)}\left[\frac{l}{l+1}\left(\frac{\tilde{E}''}{2}\right)^{l} + E_t^l - (\tilde{E}'' - E_t)^l\right]\frac{\partial E_t}{\partial d_{\tilde{i}}}. \qquad (75)$$

Since we assume $\frac{\partial E_t}{\partial d_{\tilde{i}}} \neq 0$ Eq. 75 only delivers a possible maximum if the bracket is equal to zero. The bracket equals $MAC_{l,r}(E_t) - MAC_{l,ets}(E_t)$. According to Eq. 53, it will only vanish if E_t exactly equals the solution of the single power function $i = l$ ($d_{\tilde{i}} = 0$). Starting with $d_{\tilde{i}} = 0$ an increase of $d_{\tilde{i}}$ may result in $\frac{\partial E_t}{\partial d_{\tilde{i}}} > 0$ or $\frac{\partial E_t}{\partial d_{\tilde{i}}} < 0$. For $\frac{\partial E_t}{\partial d_{\tilde{i}}} > 0$ an increase of $d_{\tilde{i}} = 0$ leads to an increase of E_t resulting in a positive value for the bracket because $MAC_{l,r}(E > E_t) - MAC_{l,ets}(E > E_t) > 0$ (see Fig. 3 for illustration). For $\frac{\partial E_t}{\partial d_{\tilde{i}}} < 0$ an increase of $d_{\tilde{i}} = 0$ leads to a decrease of E_t resulting in a negative value for the bracket because $MAC_{l,r}(E < E_t) - MAC_{l,ets}(E < E_t) < 0$ (see Fig. 3 for illustration). In both cases Eq. 75 has a negative sign.

Therefore a conical combination of weak convex power functions never changes E_t such that relative additional costs increase for any of the power functions which the conical combination consists of. This proves the Lemma 2 (Inequality 74). A conical combination of weak convex power functions never causes higher relative additional costs than the respective power functions it consists of. All findings for weak convex power functions thus also apply for a conical combination of weak convex power functions.

B Empirical data and calculations

All countries under the EU ETS are obligated to an annual reporting of a verified emissions table (VET reports). However, these reports sum up electricity generation and district heating. Moreover the classification in various companies' activities is not made clear-cut. Since our model requires a clear assignment of emissions to electricity, the monitoring is unusable for our purpose.

year	2001	2002	2003	2004	2005	2006
price index[1]	87.4	88.6	89.6	91	92.5	93.9
∅ allowance price[2],[3] **[€/t]**					18.10	17.27
electricity output[5] **[TWh]**	586.4	586.7	608.9	617.5	622.5	639.6
ETS	397.0	396.9	415.4	411.9	415.5	420.7
promoted renewables	18.1	25.0	28.4	38.5	44.0	51.5
- thereof wind power (onsore)	10.5	15.8	18.7	25.5	27.2	30.7
- thereof solar power	0.1	0.2	0.3	0.6	1.3	2.2
- thereof biomass	1.5	2.4	3.5	5.2	7.4	10.9
CO_2 emissions [kt]						
electricity[6],[7],[8]	330,582	333,422	333,172	327,128	327,339	333,613
district heating[6],[7],[8]	26,633	27,151	37,081	38,789	35,280	33,311
VET reports class I–III[9]					376,781	378,663
Coverage [%]					96.2%	96.9%
CO_2 savings [kt]						
ETS	-1,982	-4,546	11,900	11,896	13,009	10,932
promoted renewables	14,494	20,037	21,725	29,137	33,063	39,051
- thereof wind power (onsore)	8,139	12,332	13,958	18,841	19,949	22,651
- thereof solar power	59	127	234	411	939	1,638
- thereof biomass	1,226	2,051	2,794	4,162	5,803	8,646
costs [MM €]						
C_{int}					5,925	5,761
C_{int} (95 % abatement)					5,596	5,447
C_{int} (80 % abatement)					4,608	4,505
C_r[10],[11],[12]	1,142	1,688	1,804	2,522	2,406	3,136
- thereof wind power (onsore)	712	1,105	1,184	1,601	1,252	1,212
- thereof solar power	37	77	143	263	603	1,036
- thereof biomass	103	176	223	350	423	738
$e_{ets,i}$	833.8	840.1	799.8	799.8	797.1	802.2
$e_{r,i}$	793.4	779.8	775.7	757.5	747.9	733.2
- thereof wind power (onsore)	809.0	798.7	794.7	782.8	780.1	773.4
- thereof solar power	828.8	828.7	828.4	828.0	826.7	825.0
- thereof biomass	826.0	823.9	822.1	818.8	814.7	807.8

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Table 1: Emissions, abatement cost and internalized cost. Data and own calculations based on [1] Federal Statistical Office (2018), [2] German Emissions Trading Authority (2009), [3] German Emissions Trading Authority (2013), [4] Intercontinental Exchange (2018), [5] Working Group on Energy Balances (2018a), [6] Working Group on Energy Balances (2018b), [7] Federal Environment Agency (2018), [8] Statistics of the Coal Sector (2018), [9] German Emissions Trading Authority (2007–2016), [10] Information Platform of the German Transmission System Operators (2018a), [11] Information Platform of the German Transmission System Operators (2018b), [12] Fraunhofer ISE (2018)

Nevertheless, CO_2 emissions for Germany can be calculated if data from different sources is taken into account. The calculation is based on German energy balances which founded the basis for the national inventory reports in the framework of the Kyoto Protocol and are thus reliable. They are annually published by (Working Group on Energy Balances, 2018a) and reveal the resulting primary energy consumption assigned to the different technologies of electricity generation (coal, lignite, gas etc.).

2007	2008	2009	2010	2011	2012	2013	2014	2015
96.1	98.6	98.9	100	102.1	104.1	105.7	106.6	106.9
0.65	25.76	15.26	15.40	13.80	7.51	4.51[4]	6.00[4]	7.71[4]
640.6	640.7	595.7	632.5	612.2	628.6	637.7	626.7	646.9
433.1	420.8	385.7	409.6	401.1	410.8	414.7	392.7	392.4
67.0	71.1	75.1	82.3	103.1	118.3	125.7	136.9	162.7
39.7	40.6	38.5	37.6	48.3	49.9	50.8	55.9	70.9
3.1	4.4	6.6	11.7	19.6	26.1	29.6	33.9	36.1
15.9	18.9	23.0	25.2	28.0	34.3	36.3	38.3	40.6
344,211	323,829	294,283	308,115	303,903	312,756	317,535	303,319	295,685
34,275	33,026	32,041	35,330	32,717	33,192	32,151	28,386	29,090
383,608	366,613	336,616	355,761	349,706	354,962	356,059	336,666	331,050
98.7%	97.3%	96.9%	96.5%	96.3%	97.5%	98.2%	98.5%	98.1%
7,481	12,982	17,236	19,486	13,308	14,262	13,067	8,158	15,383
50,878	52,334	54,850	59,329	74,518	86,003	91,883	100,842	116,556
29,354	29,041	27,346	26,319	34,047	35,368	36,176	40,163	49,705
2,273	3,164	4,671	8,206	13,812	18,501	21,082	24,332	25,301
12,656	14,582	17,531	18,924	21,199	26,131	27,762	29,596	30,617
224	8,342	4,491	4,745	4,194	2,349	1,432	1,820	2,280
212	7,873	4,213	4,465	3,943	2,212	1,350	1,711	2,139
176	6,467	3,380	3,624	3,190	1,802	1,104	1,383	1,719
5,089	4,177	7,579	9,328	11,929	15,612	16,922	19,013	21,879
1,935	944	1,855	1,639	1,955	2,879	3,114	3,645	4,636
1,443	1,853	2,839	4,475	6,624	7,903	8,245	9,142	9,538
1,458	1,345	2,657	2,991	3,183	4,528	5,139	5,661	6,080
810.6	797.1	786.7	781.2	796.3	794.0	796.9	809.0	791.3
704.2	700.7	694.5	683.5	646.3	618.1	603.7	581.7	543.2
757.0	757.8	761.9	764.4	745.5	742.3	740.3	730.5	707.1
823.4	821.2	817.5	808.8	795.1	783.6	777.3	769.3	766.9
797.9	793.2	786.0	782.6	777.0	764.9	760.9	756.4	753.9

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This allows the calculation of CO_2 emissions E_i if the source-specific emission factors are known. These factors are used in the national inventory reports (Juhrich, 2014, e.g.) and published in detail by Federal Environment Agency (2018). For lignite they can be refined by the annual lignite statistics (Statistics of the Coal Sector, 2018).

This approach assumes that all fossil power plants are subject to emissions trading. This is an appropriate assumption as calculation results prove. Calculated emissions caused by electricity generation and district heating show a high accordance with the VET reports as coverage is quite stable (see Table 1).

Variances can be explained with slightly deviating emission factors between VET-reports and energy balances (Juhrich, 2014, pp. 779–781). In comparison to the VET reports emissions are always underestimated to about the same extent (coverage below 100 %, see Table 1). However, absolute numbers are not crucial because the analysis only requires values relative to the base period. According to this approach, the emission factor of the base period $e_{\bar{0}}$ is equal to 829.0 g/kWh.

The certificate price $p(e_{ets,i})$ is determined on an annual average. In 2005, due to lack of other data, up to the middle of September forward prices are used. Afterwards average prices of the respective December Futures of the Intercontinental Exchange (ICE) are used (German Emissions Trading Authority, 2009, 2013; Intercontinental Exchange, 2018).

The annual electricity output S_i, $S_{ets,i}$ is provided by Working Group on Energy Balances (2018b). This data also allows to calculate necessary average data for the period of observation ($\bar{S}$=621.55 TWh, $\bar{S}_{ets}$=407.87 TWh). The amount of electricity which is generated by promoted renewable energy $S_{r,i}$ can be found in the annual accounts published by Information Platform of the German Transmission System Operators (2018a). These accounts assign delivered electricity and incurred subsidies to the different renewable energy technologies (wind, solar etc.). Data with respect to the period before 2001 are provided by Wagner (2000) but do not make this assignment. Necessary information about the market value of electricity generated by RES (market factors) can be found on Information Platform of the German Transmission System Operators (2018c).