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National climate policies in times of the European Union Emissions Trading System (EU ETS)

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KIEL WORKING PAPER

**National Climate Policies
in Times of the European
Union Emissions Trading
System (EU ETS)**

A photograph showing a close-up of hands working at a desk. One hand is holding a yellow sticky note, and the other is resting on the desk. There are other yellow sticky notes, a white marker, and a small notebook on the desk. The background is slightly blurred.

No. 2052 October 2016

Johannes Burmeister, Sonja Peterson

ABSTRACT

NATIONAL CLIMATE POLICIES IN TIMES OF THE EUROPEAN UNION EMISSIONS TRADING SYSTEM (EU ETS)

Johannes Burmeister and Sonja Peterson

Given that the carbon price in the EU Emissions Trading System is only around 5€/tCO₂ while consensus about a more stringent EU climate policy is very unlikely in the near future, we explore the potential scope and optimal design of additional national climate policies in the current EU policy framework. In particular, we suggest to implement a type of carbon price floor in the national EU ETS sectors that either allows for i) shifting emissions to non-ETS sectors like housing and transport or ii) retiring EU-wide emission allowances.

In a simple theoretical framework with two countries and two sectors, we show that these two policy options are efficient up to a certain carbon price threshold. Moreover, efficiency is the highest at an optimal carbon price level equaling a weighted sum of the price differentials between ETS and non-ETS sectors. In order to determine the empirical relevance, we conduct a numerical partial equilibrium analysis of the EU carbon market in 2020. We find that Germany shows the highest potential to reduce EU-wide inefficiencies. With a price floor of 36€/tCO₂ in 2020, Germany could reduce national climate policy costs by 13% if emissions are shifted from the ETS to non-ETS sectors. If they are willing to take on additional costs by retiring emission allowances, they are able to reduce EU ETS emissions by 1.6%.

Keywords: Climate policy, EU Emission Trading System, Overlapping regulation, Carbon price floors, Abatement costs

JEL classification: Q58, H21, H23, D58

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October 11, 2016

Abstract

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1. Introduction

This paper explores the potential scope and optimal design of national climate policies in the European climate policy context. We argue that certain carbon pricing policy designs have the potential to reconcile European Union (EU) and national climate policies in an effective and cost-efficient manner.

Already in the Kyoto Protocol from 1997, the EU member states made use of the provision to fulfill their greenhouse gas (GHG) emission commitments jointly. They agreed on a collective target to reduce emissions in the first commitment period of the Protocol from 2008-2012 to 8% below 1990 levels. Also for the post-Kyoto climate policy, the EU intends to fulfill its emissions reduction targets jointly. One of the three main targets of the EU Climate and Energy Package adopted in 2009 is to cut GHG emissions by 20% by the year 2020 from 1990 levels (European Commission, 2008). Economists appreciate such a joint target since it opens the way to implement an efficient EU wide climate policy that aims at reaching this target at minimal costs.

A cornerstone of the EU's policy to combat climate change and its key tool for reducing industrial GHG emissions cost-effectively is the EU Emissions Trading System (EU ETS) launched in 2005. It covers more than 11,000 power stations and industrial plants in 31 countries, as well as airlines. It is currently the largest ETS world-wide and may thus be regarded as a very important step towards efficient (EU) climate policy.¹

Yet, the system produces large inefficiencies since only about half of EU GHG emissions are covered by the EU ETS. For the remaining emissions in non-ETS sectors such as housing, agriculture and transport, EU countries agreed to undertake national measures to reach national binding annual targets until 2020 under the so-called "Effort Sharing Decision" (European Commission, 2009). Therefore, the current EU carbon market already represents a second-best solution (Böhringer et al., 2006; Böhringer et al., 2016). Böhringer et al. (2009) analyze the inefficiencies of such second-best EU climate policies in the year 2020 with three computable general equilibrium (CGE) models. They show that the inefficiencies of separated EU carbon markets, with one ETS price and 28 implicit non-ETS prices in each member state, can be significant and leading to 25% - 50% higher abatement costs compared to the efficient solution.² One reform proposal for the EU ETS is thus to extend its scope to more sectors and regions (Edenhofer et al., 2014; Böhringer et al., 2014). It would be beneficial if there was only one carbon price in the EU in the long-run and an overall coherent European climate policy. Also, the current EU ETS targets are not very ambitious and the low carbon price of only around 5€/tCO₂ gives little incentive for technological development and structural change required to achieve the targets of the EU Roadmap 2050 (European Commission, 2011) implying GHG reductions by 80-90% relative to 1990 and with this the 2 degree targets

¹The EU ETS ensures efficiency because due to emissions trading marginal abatement costs across countries equalize and thereby the exogenous overall emissions target (the so-called cap) is reached at minimum costs.

²In reality, inefficiencies are even larger since the multitude of national policy measures outside the EU ETS do not ensure an equalization of marginal abatement costs in the non-ETS sectors in each country as in the model by Böhringer et al. (2009).

stressed in the Paris Agreement from 2015 (United Nations, 2016). Yet, every reform of the current EU system requires unanimous approval by all member states and reality has shown that it is difficult to make the EU policy more ambitious and stringent.

This is why a number of countries that regard EU policies as insufficient are discussing or implementing additional national measures to reduce emissions. Examples are the UK carbon price floor and several national carbon taxes for sectors already covered by the EU ETS.³ Most lately, also France announced the introduction of a 30 €/tCO₂ carbon price floor in the electricity sector in 2017 (The Guardian, 2016). Germany discussed an additional “climate levy” for old coal power plants (BMW, 2015) as well as a general carbon price floor (Bloomberg, 2016b). The former showed the potential to reconcile EU and national climate policies (Peterson, 2015). However, both ideas have been dismissed at least for the moment. The general problem of the current additional national policies is that they are i) not effective in terms of additional emission reductions because with an unchanged amount of EU ETS allowances any national emission reductions within the EU ETS are offset elsewhere and ii) not efficient since they drive further wedges between carbon prices. In this context, Böhringer et al. (2008) and Heindl et al. (2014) show that an additional national carbon tax in the ETS sector in one or more countries further increase EU-wide inefficiencies. Both papers impose a tax on top of the allowance price in the ETS sector (which is equivalent to a carbon price floor for the ETS sector) in one region while keeping the overall joint emission quantity target constant. On the one hand, the higher carbon price in the taxing region leads to an increase of overall abatement costs. On the other hand, firms in the taxing region emit less and sell their excess emission allowances, resulting in a fall of the EU allowance price. This leads to a decrease of overall abatement costs in the EU ETS because non-taxing regions face a lower price and abate less emissions. The authors find that the net effect is always an increase in overall abatement costs and thus higher inefficiencies. The non-ETS sector is disregarded because it is not affected by the tax policy in the ETS sector. Heindl et al. (2014) show that the general efficiency results also hold when allowing for uncertainty and correlation of abatement costs across countries as well as different country sizes in terms of emissions.

As a result, the only way to increase abatement efforts by single, ambitious EU countries seems to be to reduce more emissions in their non-ETS sectors that are not linked to the EU ETS. The question is whether there are no advisable possibilities to pursue more ambitious climate policies in their ETS sectors. Motivated by the potential of additional policies to close the gap between (implicit) carbon prices in the non-ETS sectors and the ETS allowance price as well as by the idea of the German climate levy that included retiring EU ETS allowances, our paper discusses two new policy designs. These account for the possibility to i) shift emission allowances between ETS and non-ETS sectors and ii) retire emission allowances and thereby reducing overall EU emissions. By doing so, we show that national climate policies - although interfering with the EU ETS - can be effective and efficient.

This paper builds on the work by Böhringer et al. (2008) and Heindl et al. (2014) but

³For example, Sweden, Finland and Denmark tax sectors which are already covered by the EU ETS.

allowing for the adjustment of emission targets in either the non-ETS or ETS sector as motivated above. We contribute to this literature by adding alternative carbon pricing policy designs and thereby contradicting previous efficiency results. It is also linked to the extensive literature on price versus quantity constraints in emissions regulation and the combination of both i.e. so-called hybrid approaches to emissions pricing such as price floors within an emission trading scheme (e.g. Weitzman, 1974; Roberts and Spence, 1976; Unold and Requate, 2001; Mandell, 2008; Wood and Jotzo, 2011; Abrell and Rausch, 2016).

The paper is structured as follows. In section 2, we set up the stylized theoretical framework of a simple two country and two sector model in order to derive the optimal design of our two policy designs analytically. In section 3, we test our theoretical findings empirically and conduct a numerical partial equilibrium analysis of the EU carbon market in 2020. After discussing the validity of our empirical findings for the EU, we summarize our results and conclude.

2. Theoretical analysis

We use a simple partial equilibrium framework for two countries 1 and 2 in order to evaluate the effectiveness and efficiency of additional national climate policies in the EU climate policy framework. Both countries have to abate emissions in two sectors. One sector is regulated by an emissions trading scheme with a fixed overall joint target (ETS sector). The other sector is regulated by individual carbon taxes for each country in order to meet a fixed national quantity target (non-ETS sector).

We differentiate between two national policy cases. In the first policy case, country 1 is eager to increase abatement in the ETS sector by introducing a carbon price floor in the form of an additional tax or extra fee for emitting firms on top of the ETS allowance price. As a consequence, firms in country 1 emit less and sell their excess emission allowances which increases the allowance supply. Normally, this would lead to a falling allowance price and higher emissions in the ETS sector i.e. to a counter-effect. However, in our stylized analysis, we assume that the government which introduced the policy uses the tax (or fee) revenue in order to buy these excess allowances and to retire them. While country 1 increases abatement in the ETS sector, it is allowed to relax its abatement efforts in the non-ETS sector by exactly the same amount. Thus, in the first policy case, overall emissions remain the same but one country shifts emissions from the ETS to the non-ETS sector. Therefore, this first policy case is not effective but its efficiency will be investigated.

In the second policy case, country 1 again increases abatement efforts in the ETS sector. However, in contrast to the first policy case, no shift of emissions to the non-ETS sector takes place. The government just buys the excess allowances and retires them such that the overall emission target decreases.⁴ This policy is effective since

⁴In the spirit of the "climate levy" for old coal power plants proposed in Germany in mid 2015 (BMW, 2015).

overall emissions are reduced but its efficiency will be investigated. In the following, we will formulate the benchmark situation and two policy cases formally.

2.1. Efficiency and Benchmark Solution

Both countries have emission abatement possibilities associated with certain costs that can be represented by a cost function $c(a)$ with a being the abated emissions quantity (e.g. Mt CO₂ eq.). The cost function is assumed to be strictly monotonically increasing and convex, i.e.

$$c'(a) > 0$$

and

$$c''(a) > 0.$$

Since we have two countries indexed by $i = 1, 2$ and two sectors, we denote $c_i(x_i)$ and $c_i(y_i)$ as the cost functions in the ETS and non-ETS sector with actual abated emissions quantities x_i and y_i , respectively. For simplicity, we assume that ex-ante emission rights allocations are grandfathered. Thus, both countries have a joint emissions abatement target

$$z_x = x_1^T + x_2^T \quad (1)$$

for the ETS sector with ex-ante abatement quantities x_1^T and x_2^T .⁵ Within the joint target z_x , countries i can trade emissions allowances as needed because their actual abatement x_i may be either greater or less than ex-ante allocated quantities x_i^T depending on their abatement possibilities. Hence, we denote s as the amount of allowances sold from one country to the other which can be either positive or negative. Cost efficiency for the ETS sector is characterized by the cost-minimizing allocation of abatement between the two countries under the emissions trading scheme. This leads to the first order conditions that marginal abatement costs equalize across the two countries, i.e.

$$\rho = c'_1(\tilde{x}_1) = c'_2(\tilde{x}_2), \quad (2)$$

with \tilde{x}_i representing the equilibrium abatement quantities in the ETS and resulting equilibrium ETS market price ρ . Thus,

$$s = \tilde{x}_1 - x_1 = -(\tilde{x}_2 - x_2), \quad (3)$$

whereas a positive sign denotes exports and a negative imports.

Note that this is not the overall cost-efficient equilibrium since we are disregarding the non-ETS sector up to now. Overall cost-efficiency implies that total marginal abatement costs equalize across *all* sectors in both countries. Regarding the non-ETS sector, there does not exist a joint abatement target but only single national targets z_{y1} and z_{y2} for

⁵Note that to simplify notation we define the allocation in terms of abatement and not as an emission target. If e_i is the emission target and e_i^0 are business-as-usual emissions, then $x_i^T := e_i^0 - e_i$.

each country. For simplicity, we assume that these single targets are met by national carbon taxes such that

$$z_{y_1} = \tilde{y}_1 \quad (4)$$

and

$$z_{y_2} = \tilde{y}_2 \quad (5)$$

(cf. Böhringer et al., 2016, p. 505). Therefore, the overall abatement target across all countries and sectors is given by

$$z = z_x + z_{y_1} + z_{y_2} = \tilde{x}_1 + \tilde{y}_1 + \tilde{x}_2 + \tilde{y}_2. \quad (6)$$

Finally, overall cost-efficiency implies that total abatement costs are minimized with respect to the overall target z . Thus, cost-efficiency leads to the first-order conditions that marginal abatement costs equalize across all countries and sectors, i.e.

$$p^* = c'_1(x_1^*) = c'_1(y_1^*) = c'_2(x_2^*) = c'_2(y_2^*), \quad (7)$$

with optimal abatement quantities x_1^* , x_2^* , y_1^* and y_2^* . p^* denotes the optimal value of the marginal abatement unit or allowance price. It is important to note that this efficient first best solution is only reached by coincidence in our above introduced setting due to the separated carbon market. The first best solution could only be reached if all sectors are covered by the emissions trading scheme of the ETS sector. Therefore, our benchmark situation is the second best solution with three potentially different carbon prices given by

$$\begin{aligned} \rho &= c'_1(\tilde{x}_1) = c'_2(\tilde{x}_2) \\ \pi_1 &= c'_1(\tilde{y}_1) \\ \pi_2 &= c'_2(\tilde{y}_2), \end{aligned} \quad (8)$$

with the carbon price under emissions trading in the ETS sectors ρ and two national prices π_1 and π_2 in the non-ETS sectors. The latter can be regarded as the level of national carbon taxes in order to achieve the non-ETS target.

For simplicity, we define the abatement cost curves as second-order polynomials

$$c_i(x_i) = \frac{1}{2}a_i x_i^2$$

and

$$c_i(y_i) = \frac{1}{2}b_i y_i^2.$$

This leads to linear marginal abatement cost (MAC) curves

$$c'_i(x_i) = a_i x_i$$

and

$$c'_i(y_i) = b_i y_i,$$

with slope parameters a_i and b_i .⁶ In order to obtain the first best solution of the two country and two sector model, we simply need to solve the first order conditions (7) under the overall quantity target (6) i.e. the linear equation system

$$\begin{aligned} p &= a_1 x_1 = b_1 y_1 = a_2 x_2 = b_2 y_2 \\ z &= x_1 + y_1 + x_2 + y_2 \end{aligned} \quad (9)$$

for the unknowns x_1, x_2, y_1, y_2 and p . The result leads to optimal quantities $x_1^*, x_2^*, y_1^*, y_2^*$ and the optimal price p^* given in Appendix A.1. Figure 1 shows the MAC curves for our simple two country model.

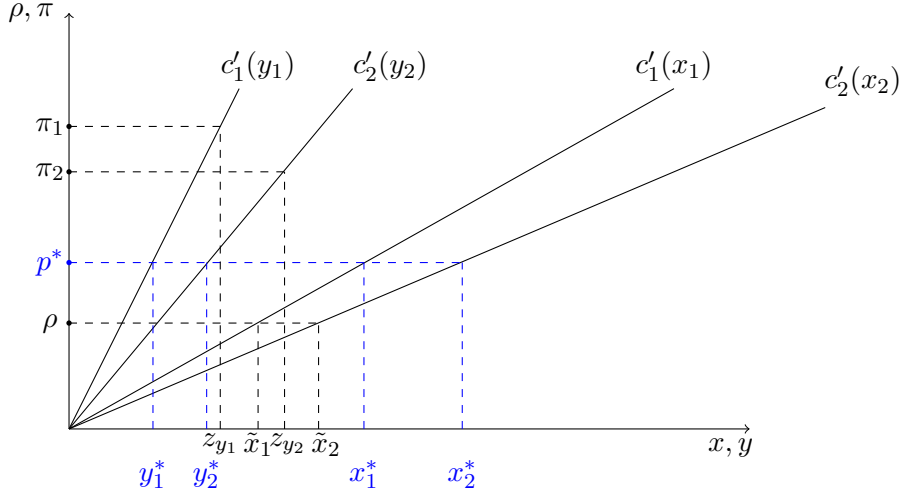


Figure 1: Marginal abatement cost curves for the two country and two sector model.

Empirically, one expects higher costs for the same abatement quantity in the non-ETS sector because it represents sectors like transportation or housing where it is more costly to abate emissions. Thus, the non-ETS MAC curves are drawn left to the ETS MAC curves. Since the ETS-sector is regulated by an emissions trading scheme, marginal abatement costs equalize resulting in one carbon price for this sector in both countries denoted by ρ . The corresponding abatement quantities in both countries are \tilde{x}_1 and \tilde{x}_2 , respectively. On the other hand, the two countries face different abatement prices in the non-ETS sector denoted by π_1 and π_2 . The corresponding abatement quantities are z_{y_1} and z_{y_2} , respectively. The price p^* and its corresponding quantities represent the overall efficient first best solution. However, note that this efficient solution is not the benchmark situation. The benchmark situation is the (inefficient) second best solution with separated carbon markets since the emissions trading scheme only applies for one sector. The respective benchmark abatement levels are $\tilde{x}_1, \tilde{x}_2, z_{y_1}, z_{y_2}$ and prices ρ, π_1 and π_2 . We calculate the inefficiency I of this second best benchmark situation as the

⁶In this simple theoretical analysis, we refrain from MAC curves with second or third order polynomials. However, we account for convexity of marginal abatement costs in our quantitative analysis.

quotient of total inefficient costs A and efficient costs K , i.e.

$$I_{bmk} = \frac{A_{bmk}}{K_{bmk}}. \quad (10)$$

Total inefficient costs are simply the sum of the triangle areas under the MACs for each sector and country, i.e.

$$\begin{aligned} A_{bmk} &= \int_0^{\tilde{x}_1} a_1 x_1 \, dx_1 + \int_0^{z_{y_1}} b_1 y_1 \, dy_1 + \int_0^{\tilde{x}_2} a_2 x_2 \, dx_2 + \int_0^{z_{y_2}} b_2 y_2 \, dy_2 \\ &= \frac{1}{2} a_1 \tilde{x}_1^2 + \frac{1}{2} b_1 z_{y_1}^2 + \frac{1}{2} a_2 \tilde{x}_2^2 + \frac{1}{2} b_2 z_{y_2}^2. \end{aligned} \quad (11)$$

with \tilde{x}_i defined in Appendix A.2.

Total efficient costs are

$$K_{bmk} = \frac{1}{2} a_1 x_1^{*2} + \frac{1}{2} b_1 y_1^{*2} + \frac{1}{2} a_2 x_2^{*2} + \frac{1}{2} b_2 y_2^{*2},$$

with efficient quantities as given in Appendix A.1.

2.2. Policy 1

We now turn to the first policy case and evaluate its efficiency. It is obvious that this policy is ineffective since one country only shifts emissions from the ETS sector to the non-ETS sector while overall emissions remain the same. However, overall inefficiency I might be reduced which then could still justify the policy. Thus, we evaluate whether the overall inefficiency policy is less than in the benchmark situation. For this we define Δ_{pol1} as the difference of the cost of policy 1 to the costs in the benchmark. Efficient costs remain the same as the overall target (6) does not change. The question is thus whether Δ_{pol1} is negative:

$$\begin{aligned} I_{pol1} &= \frac{A_{pol1}}{K_{bmk}} \stackrel{?}{<} I_{bmk} = \frac{A_{bmk}}{K_{bmk}} \\ \Leftrightarrow \Delta_{pol1} &:= A_{pol1} - A_{bmk} \stackrel{?}{<} 0. \end{aligned} \quad (12)$$

Therefore, the efficient price p^* and its corresponding quantities x_1^* , x_2^* , y_1^* and y_2^* in Figure 1 remain unchanged. If one country increases abatement efforts in the ETS sector but accordingly reduces them in the non-ETS sector, new total inefficient costs A_{pol1} are

$$\begin{aligned} A_{pol1} = A_{bmk} + \Delta_{pol1} &= \int_0^{\tilde{x}_1 + \delta_1} a_1 x_1 \, dx_1 + \int_0^{z_{y_1} - \delta_1} b_1 y_1 \, dy_1 + \int_0^{\tilde{x}_2} a_2 x_2 \, dx_2 + \\ &\quad \int_0^{z_{y_2}} b_2 y_2 \, dy_2, \end{aligned}$$

with δ_1 as the additional abatement quantity in the ETS sector of country 1. We then have to analyze whether

$$\Delta_{pol1} = \int_{\tilde{x}_1}^{\tilde{x}_1 + \delta_1} a_1 x_1 dx_1 + \int_{z_{y1}}^{z_{y1} - \delta_1} b_1 y_1 dy_1 \stackrel{?}{<} 0. \quad (13)$$

Solving the integrals leads to

$$\Delta_{pol1} = \frac{1}{2} a_1 [(\tilde{x}_1 + \delta_1)^2 - \tilde{x}_1^2] + \frac{1}{2} b_1 [(z_{y1} - \delta_1)^2 - z_{y1}^2] \stackrel{?}{<} 0. \quad (14)$$

Finally, solving (14) for the additional abatement effort δ_1 and assuming that the non-ETS price π_1 is higher than the ETS price ρ leads to the inequality condition

$$\delta_1 < \frac{2(\pi_1 - \rho)}{a_1 + b_1}, \quad (15)$$

which is shown in Appendix A.3. This means that the country with additional abatement efforts should choose an additional abatement quantity δ_1 that is less than twice the price difference between its non-ETS sector (price π_1) and ETS-sector (price ρ) divided by the sum of slope parameters of both sectors' MACs. We assume that the additional abatement effort in the ETS sector of one country is realized by introducing a quantity tax τ_i per tCO₂ resulting in an abatement level of \hat{x}_1 . Then the inequality condition (15) for the additional abatement quantity can be transformed into a condition for the tax level τ_i . Inserting the first order condition without tax,

$$c'(\tilde{x}_1) = \rho = a_1 \tilde{x}_1 \quad (16)$$

into the one with tax

$$c'(\hat{x}_1) = \rho + \tau_1 = a_1 \hat{x}_1 \quad (17)$$

leads to

$$\delta_1 = \hat{x}_1 - \tilde{x}_1 = \frac{\rho + \tau_1}{a_1} - \frac{\rho}{a_1} = \frac{\tau_1}{a_1} \quad (18)$$

Therefore, in order to reduce inefficiency I of the carbon market the tax τ_1 needs to fulfill the inequality condition

$$\tau_1 < \frac{2a_1(\pi_1 - \rho)}{a_1 + b_1}. \quad (19)$$

Further, the optimal tax level is given by the optimality condition

$$\frac{\partial \Delta_{pol1}}{\partial \tau_1} = \tilde{x}_1 + \frac{\tau_1}{a_1} - \frac{b_1 z_{y1}}{a_1} + \frac{b_1}{a_1^2} \tau_1 \stackrel{!}{=} 0 \quad (20)$$

leading to

$$\tau_1 = \frac{a_1(\pi_1 - \rho)}{a_1 + b_1}, \quad (21)$$

which is shown in Appendix A.4.

Figure 2 shows the inefficiency analysis of the first policy case.

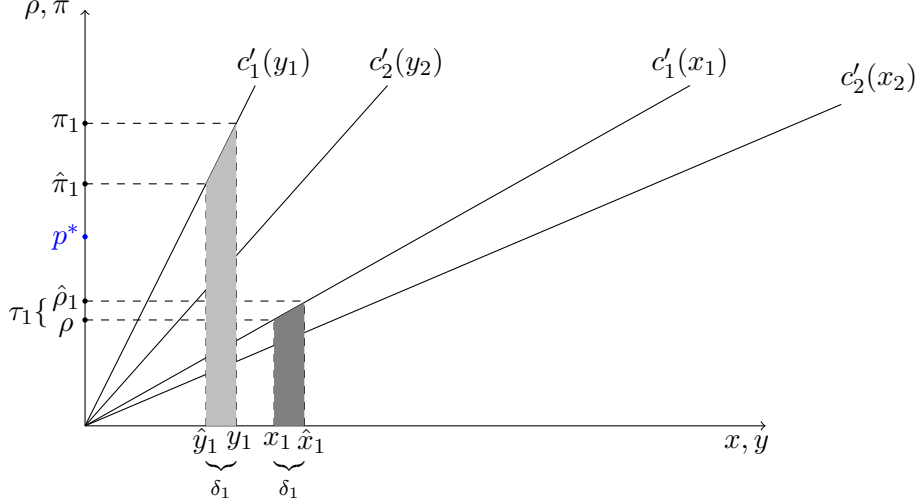


Figure 2: Inefficiency analysis of the first policy case.

As stated above, the second country is not affected by the policy in the first country since additional abatement effort δ_1 in the ETS sector is accordingly reduced in the non-ETS sector. If inequality condition (19) holds, the additional costs in the ETS sector (dark grey shaded area) are less than the saved costs in the non-ETS sector (light grey shaded area). Thus, overall inefficiency of this two-country economy would be reduced due to the additional national climate policy of the first country.

2.3. Policy 2

We now turn to the second policy case. Again, one of the two countries increases its abatement effort in the ETS sector by an additional tax (or fee). However, this time no adjustment of the abatement efforts in the non-ETS sector takes place. The government buys the excess allowances of the ETS sector and just retires them. Consequently, overall abatement target before the policy (6), is increased to

$$\hat{z} = z + \delta_1 = \tilde{x}_1 + \delta_1 + \tilde{y}_1 + \tilde{x}_2 + \tilde{y}_2 \quad (22)$$

after the policy. Hence, in contrast to policy 1, policy 2 is effective and reduces overall emissions. The question remains whether it is also efficient and reduces overall abatement costs of the two countries compared to the benchmark situation. The inefficiency in the benchmark situation I_{bmk} is again (10), namely total inefficient costs A_{bmk} over efficient

costs K_{bmk} . We again evaluate the inefficiency before and after the policy i.e.

$$\begin{aligned}
I_{pol2} &= \frac{A_{pol2}}{K_{pol2}} \stackrel{?}{<} I_{bmk} = \frac{A_{bmk}}{K_{bmk}} \\
\Rightarrow \frac{A_{bmk} + \Delta_{pol2}}{K_{bmk} + \Theta} &\stackrel{?}{<} \frac{A_{bmk}}{K_{bmk}} \\
\Rightarrow \frac{A_{bmk} + \Delta_{pol2}}{A_{bmk}} &\stackrel{?}{<} \frac{K_{bmk} + \Theta}{K_{bmk}} .
\end{aligned} \tag{23}$$

Note that this time efficient total costs before the policy K_{bmk} differ from total costs after the policy $K_{bmk} + \Theta$, since overall abatement target z changed to \hat{z} . If one country increases abatement efforts in the ETS sector, new total inefficient costs A_{pol2} are

$$\begin{aligned}
A_{pol2} = A_{bmk} + \Delta_{pol2} &= \int_0^{\tilde{x}_1 + \delta_1} a_1 x_1 dx_1 + \int_0^{z_{y_1}} b_1 y_1 dy_1 + \int_0^{\tilde{x}_2} a_2 x_2 dx_2 + \\
&\quad \int_0^{z_{y_2}} b_2 y_2 dy_2 \\
&= \frac{1}{2} a_1 (\tilde{x}_1 + \delta)^2 + \frac{1}{2} b_1 z_{y_1}^2 + \frac{1}{2} a_2 \tilde{x}_2^2 + \frac{1}{2} b_2 z_{y_2}^2 .
\end{aligned}$$

Total inefficient costs in the benchmark situation are given by (11). Therefore, the left hand side in the last line of (23) leads to

$$\begin{aligned}
\frac{A_{bmk} + \Delta_{pol2}}{A_{bmk}} &= \frac{\frac{1}{2} a_1 (\tilde{x}_1 + \delta)^2 + \frac{1}{2} b_1 z_{y_1}^2 + \frac{1}{2} a_2 \tilde{x}_2^2 + \frac{1}{2} b_2 z_{y_2}^2}{\frac{1}{2} a_1 \tilde{x}_1^2 + \frac{1}{2} b_1 z_{y_1}^2 + \frac{1}{2} a_2 \tilde{x}_2^2 + \frac{1}{2} b_2 z_{y_2}^2} \\
&= 1 + \frac{a_1 \delta_1^2 + 2a_1 \tilde{x}_1 \delta_1}{a_1 \tilde{x}_1^2 + b_1 z_{y_1}^2 + a_2 \tilde{x}_2^2 + b_2 z_{y_2}^2} .
\end{aligned}$$

Inserting the efficient ETS price from Appendix A.2 leads to

$$\frac{A_{bmk} + \Delta_{pol2}}{A_{bmk}} = 1 + \frac{a_1 \delta_1^2 + 2\rho \delta_1}{\rho z_x + \pi_1 z_{y_1} + \pi_2 z_{y_2}} ,$$

which is shown in Appendix A.6.

Now, we may look at the right hand side of (23). The new total efficient costs $K_{bmk} + \Theta$ are

$$\begin{aligned}
K_{bmk} + \Theta &= \int_0^{\hat{x}_1^*} a_1 x_1 dx_1 + \int_0^{\hat{y}_1^*} b_1 y_1 dy_1 + \int_0^{\hat{x}_2^*} a_2 x_2 dx_2 + \int_0^{\hat{y}_2^*} b_2 y_2 dy_2 \\
&= \frac{1}{2} a_1 \hat{x}_1^{*2} + \frac{1}{2} b_1 \hat{y}_1^{*2} + \frac{1}{2} a_2 \hat{x}_2^{*2} + \frac{1}{2} b_2 \hat{y}_2^{*2} .
\end{aligned}$$

By inserting new efficient equilibrium quantities given in Appendix A.5, we obtain

$$\begin{aligned} K_{bmk} + \Theta &= \frac{1}{2}a_1\left(\frac{(z + \delta_1)a_2b_1b_2}{\gamma}\right)^2 + \frac{1}{2}b_1\left(\frac{(z + \delta_1)a_1a_2b_2}{\gamma}\right)^2 \\ &+ \frac{1}{2}a_2\left(\frac{(z + \delta_1)a_1b_1b_2}{\gamma}\right)^2 + \frac{1}{2}b_2\left(\frac{(z + \delta_1)a_1a_2b_1}{\gamma}\right)^2, \end{aligned}$$

with

$$\gamma = a_1a_2b_1 + a_1a_2b_2 + a_1b_1b_2 + a_2b_1b_2.$$

Thus, for the right hand side in the last line of (23), we obtain

$$\frac{K_{bmk} + \Theta}{K_{bmk}} = \frac{(z + \delta_1)^2}{z^2},$$

which is shown in Appendix A.7.

Hence, policy 2 increases overall efficiency of this two country and two sector carbon market model if the inequality

$$\frac{(z + \delta_1)^2}{z^2} > 1 + \frac{a_1\delta_1^2 + 2\rho\delta_1}{\rho z_x + \pi_1 z_{y_1} + \pi_2 z_{y_2}} \quad (24)$$

holds. Finally, solving (24) for the additional abatement quantity δ_1 leads to

$$\delta_1 < \frac{2Qz - 2\rho z^2}{a_1 z^2 - Q},$$

with

$$Q = \rho z_x + \pi_1 z_{y_1} + \pi_2 z_{y_2},$$

which is shown in Appendix A.8. Using (18), we find that for policy 2 the tax level introduced in country 1 should fulfill

$$\tau_1 < \frac{2a_1(\frac{Q}{z} - \rho)}{a_1 - \frac{Q}{z^2}}$$

in order to increase overall efficiency (threshold tax level). The optimal tax level is given by

$$\tau_1 = \frac{a_1(\frac{Q}{z} - \rho)}{a_1 - \frac{Q}{z^2}}.$$

3. Empirical Analysis

We now extend our stylized two country model and conduct a numerical partial equilibrium analysis of the EU carbon market. The question is whether it is effective and efficient if a certain region introduces a national carbon tax in the ETS sector. In order to compare total abatement costs in the EU benchmark situation with total costs in the presence of an additional national carbon tax, we use estimates of MAC curves for each region. We follow Ellerman and Decaux (1998), Klepper and Peterson (2006) and Böhringer et al. (2008), among others, and obtain a sequence of price and abatement quantity combinations for each EU region from a computable general equilibrium (CGE) model solution in 2020. A brief description of the CGE model and its calibration to actual EU emission reduction targets for 2020 is presented in the next section. After approximating the MAC curves by least squares, we are able to compare estimates of total abatement costs of different national tax policy scenarios. As in chapter 2, we differentiate between a national policy that allows for shifting emissions from the ETS to the non-ETS sector (policy 1) and a policy in which the government buys the excess emissions allowances and retires them such that the overall emission target in the EU decreases (policy 2).

3.1. Generation of MAC curves

For the approximation of MAC curves in the ETS and non-ETS sectors and each EU region, we generate a sequence of emission quantities and CO₂ prices from the Dynamic Applied Regional Trade (DART) model. DART is a multi-region, multi-sector recursive dynamic computable general equilibrium (CGE) model of the world economy including 21 EU regions (see Table 3, Appendix B).⁷ The economy in each region is modeled as a competitive economy with flexible prices and market clearing. All regions are connected through bilateral trade flows. The model is calibrated to the GTAP8 database that represents production, trade as well as emissions data for 2007 (The Global Trade Analysis Project, 2012). The major exogenous drivers of the dynamic structure are the GDP projections, the savings rate, the depreciation rate, and the rate of change of the population. For each year (and region), the representative agent's labor productivity is adjusted such that the exogenous GDP path taken from the OECD, 2014, is reached. The model horizon here is the year 2020.

GTAP data for sectoral CO₂ emissions of fossil fuels resulting from final demand and intermediate production input demand are linked to the consumption and production structure of DART. If the model is solved with no emission constraints, emissions evolve in a business-as-usual (BaU) fashion over time. In this case, there is no price for emitting CO₂. However, if a quantity target is exogenously set, the model returns an implicit (shadow) price for CO₂ emissions due to the constraint. By simultaneously varying

⁷For descriptions of DART see Appendix of Weitzel et al. (2012) and Weitzel (2010). Besides the EU regions, the rest of world is aggregated to nine regions: North America, Latin America, India, China, Former Soviet Union, Pacific Asia, Middle East and Northern Africa, Subsaharan Africa and Rest of Annex B countries.

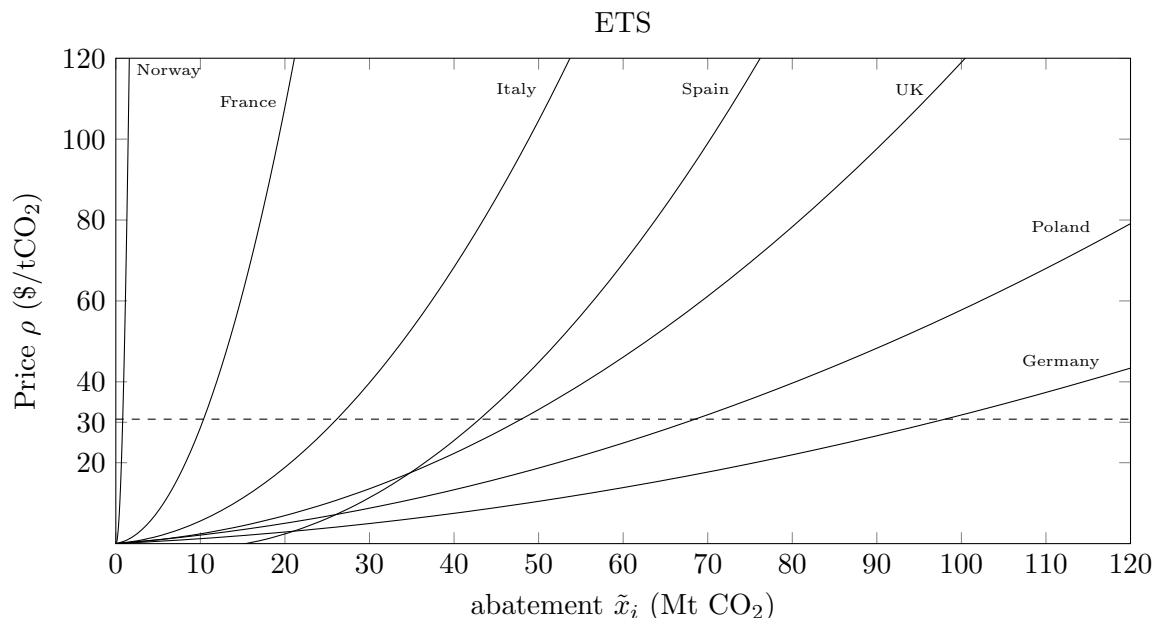
this quantity constraint for the EU regions in ETS and non-ETS sectors, we generate a sequence of CO₂ price and abatement quantity combinations in 2020.⁸ In contrast to section 2 where we assumed linear MAC curves to reduce complexity, we now assume more realistic non-linear MAC curves of the form

$$\rho = c'_i(x_i) = a_i x_i^2 + b_i x_i \quad (25)$$

and

$$\pi_i = c'_i(y_i) = c_i y_i^2 + d_i y_i \quad (26)$$

for $i = 1, \dots, 21$ EU regions. Inserting these equilibrium abatement quantities \tilde{x}_i and \tilde{y}_i and respective CO₂ prices ρ and π_i in (25) and (26), we fit the MAC curves by least-squares to obtain estimates for the slope parameters \hat{a}_i , \hat{b}_i , \hat{c}_i and \hat{d}_i . The regression results are given in Table 4, Appendix B. With few exceptions the estimated parameters are significant at the 0.1%-level. Figure 3 shows MAC curves for selected EU regions and both the aggregated ETS and non-ETS sectors.



⁸For the emission constraints in the rest of the world, it is assumed that countries fulfill their emission targets stated in the “Copenhagen Agreement” from 2012.

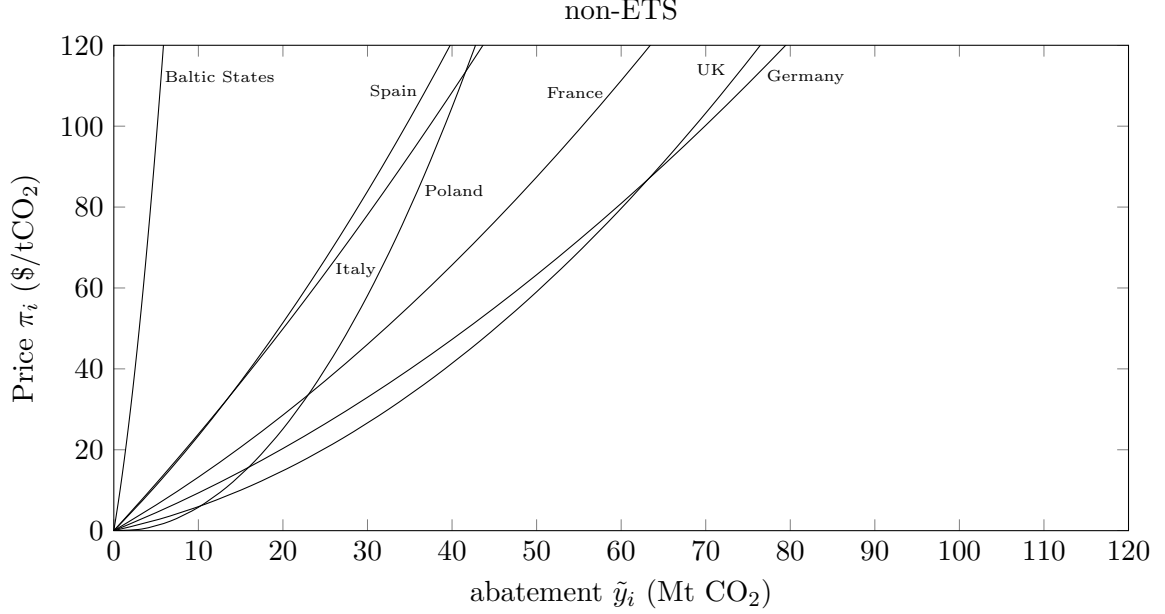


Figure 3: MAC curves across selected EU regions in 2020 for the ETS and non-ETS sectors.

As assumed in our stylized framework in section 2, it is generally cheaper to abate emissions in ETS sectors than in non-ETS sectors. This is indicated by the flatter MAC curves of the ETS sectors. Abatement in the ETS sectors is the cheapest in Germany and most expensive in Norway whereas abatement in the non-ETS sectors is the cheapest in the UK and most expensive in the Baltic States. Moreover, marginal abatement costs also differ across the different ETS and non-ETS sectors. Figure 3, Appendix C shows selected MAC curves of different sectors in Germany, France and the UK. For all three countries, the electricity sector shows the cheapest abatement possibilities within the ETS sectors and the mobility sector within the non-ETS sectors. The chemical sector shows the most expensive abatement possibilities within the ETS sectors in Germany and France. In the UK, it is the most expensive to abate emissions in the refined oil products sector. Within the non-ETS sectors, other light industries like food products and textiles in Germany, the agricultural sector in France and natural gas production in the UK show the most expensive abatement possibilities. For all countries, we neglect the non-ETS sectors “coal” and “crude oil production” because without practically any abatement options, emissions reduction in these sectors is so expensive that their MAC curves cannot be distinguished from the y-axis.

3.2. Partial equilibrium analysis of the EU carbon market

In the first step we specify the current EU ETS and non-ETS targets. We apply actual relative yearly emission reduction targets of the EU as quantity constraints for both sectors in DART. The business-as-usual (BaU) emissions less the emission targets then

lead to abatement targets in 2020 with respective CO₂ prices. Table 3 in Appendix B summarizes the EU carbon market data of the European Energy Agency, 2016, underlying the policy simulations. The EU-wide relative emission reduction targets for the ETS and non-ETS sector in 2020 result in 24% and 13% lower emission levels compared to 2007 (the base year of the DART model), respectively.

Given the estimates of slope parameters and abatement targets, we are then able to solve the partial equilibrium model for the benchmark situation with a fixed overall target for the ETS sector and individual national targets for the non-ETS sector. That is, we minimize total abatement costs only subject to the EU ETS target z_x whereas single targets for the non-ETS sectors are exogenous and assumed to be met by national carbon taxes, i.e.

$$\begin{aligned} \min_{x_i, y_i} \quad & \sum_i c(x_i) + c(y_i) \\ \text{s.t.} \quad & \sum_i x_i = z_x \quad \wedge \quad y_i = z_{y_i} \quad \forall i. \end{aligned} \tag{27}$$

The resulting benchmark price ρ for the EU ETS in 2020 is around 27 €/tCO₂ (see dashed line in Figure 3).⁹ The price is well in line with what other energy-economy models predict for the year 2020 (cf. Knopf et al., 2013, p.22), though significantly higher than the actual ETS allowance price of around 5 € and medium-term predictions of a majority of experts (ZEW, 2016). For the discussion of possible reasons for the deviation between the actual price and predictions of energy-economy models, we refer to Edenhofer et al. (2014, p.14f.). National non-ETS prices π_i range from 25 € in Italy up to 112 € in Denmark. In order to evaluate the inefficiency of the EU carbon market I_{bmk} as total inefficient costs over efficient costs, we include the non-ETS sector in the cap-and-trade system and solve the model again for the overall efficient solution

$$\min_{x_i, y_i} \sum_i c(x_i) + c(y_i) \quad \text{s.t.} \quad \sum_i (x_i + y_i) = z. \tag{28}$$

The inefficiency due to the separated carbon market leads to 25% higher costs compared to a carbon market with all sectors included in the ETS ($I_{bmk} = 1.25$) which is within the range of results in Böhringer et al. (2008). The overall efficient price is 42 €.

We now turn to our two policy cases and introduce a carbon tax on top of the ETS price that we vary from 1 to 50 € in each of the 21 EU regions. The results of the policies are shown in Table 1 and 2, respectively. Note that the tables show the overall results for only one country i introducing the policy, not for all countries introducing the policy at the same time. Regarding policy 1, in which the country shifts its additional emissions to the non-ETS sector, the optimal carbon price floors that minimize EU abatement costs vary between 31.8 € in Poland and 83.5 € in Sweden.¹⁰ The resulting EU-wide inefficiency gains range from 0.1 p.p. in Hungary and Ireland to 3.3 p.p. in the “rest of

⁹Since the GTAP data is in dollars, we convert prices with the exchange rate 1\$=0.89€. In the following, we skip the “€/tCO₂” dimension.

¹⁰The optimal ETS carbon price floor is the old EU-wide ETS price plus the additional optimal tax.

EU” region¹¹. Except for the “rest of EU”, Germany shows the highest potential for reducing inefficiencies of the EU carbon market, followed by the Netherlands and Spain. Any carbon price floor in Italy is inefficient and increases inefficiencies. By introducing a carbon price floor of 36.3€ in 2020, Germany is able to reduce overall inefficiencies by 2.4 p.p. Further, the shift of emissions due to the price floor in Germany lowers EU-wide emissions in the ETS sector by 1.7% while increasing emissions in the non-ETS sector by 0.9%. However, note that the absolute emission level remains constant in the EU since policy 1 is ineffective (though efficient). From a national viewpoint, the shift lowers emissions in the ETS sector by 8.3% while increasing emissions in the non-ETS sector by 7.2% in Germany.

	Policy 1							
	Carbon price floor in €	ΔI in p.p.	Δ cost in EU in %	Δ cost in country in %	EU-wide emission change in ETS in %	EU-wide emission change in n-ETS in %	National emission change in ETS in %	National emission change in n-ETS in %
Austria	64.8	-0.5	-0.4	-17.2	-0.2	0.1	-22.2	5.6
Baltic states	39.0	-0.1	-0.1	-11.4	-0.1	0.1	-10.8	5.6
Belgium	58.5	-1.2	-1.0	-22.9	-0.4	0.2	-11.1	7.5
Czech Rep.	38.1	-1.4	-1.1	-24.5	-0.4	0.3	-10.5	18.2
Denmark	72.8	-0.9	-0.7	-22.7	-0.2	0.1	-25.4	7.0
Finland	43.4	-0.7	-0.6	-31.5	-0.2	0.1	-13.9	9.9
France	55.0	-0.6	-0.5	-6.4	-0.3	0.2	-9.3	1.7
Germany	36.3	-2.4	-1.8	-12.6	-1.7	0.9	-8.3	7.2
Greece	46.1	-0.8	-0.6	-7.3	-0.5	0.4	-16.2	5.3
Hungary	38.1	-0.1	-0.0	-5.4	-0.1	0.0	-5.8	2.7
Ireland	45.2	-0.1	-0.0	-5.4	-0.0	0.0	-8.3	1.9
Italy	27.4	-	-	0.4	-	-	-	-
Netherlands	82.6	-2.2	-1.8	-20.4	-0.5	0.3	-11.9	6.9
Norway	60.3	-0.1	-0.0	-3.7	-0.0	0.0	-9.1	0.7
Poland	31.8	-0.7	-0.5	-6.8	-0.5	0.3	-3.8	7.4
Portugal	41.6	-0.2	-0.1	-11.9	-0.1	0.1	-8.1	3.8
Rest of EU	45.2	-3.3	-2.7	-28.5	-1.0	0.6	-11.9	15.2
Slovakia	46.1	-0.5	-0.4	-25.8	-0.1	0.1	-13.6	15.3
Spain	45.2	-1.6	-1.4	-17.2	-0.7	0.5	-9.9	5.8
Sweden	83.5	-0.6	-0.5	-20.3	-0.1	0.1	-20.3	5.2
UK	39.0	-1.1	-0.9	-9.2	-0.8	0.5	-5.4	3.8

Table 1: Policy simulation results for shifting emissions from the ETS to non-ETS sector. In Benchmark: ETS price 27.4€, Efficient price 41.9€ and Inefficiency I 1.25.

Regarding policy 2, which reduces the absolute emission level in the EU, optimal carbon price floors do not vary much across regions and range from 52€ to 55€. The resulting EU-wide efficiency gains range from 0.03 p.p. in Norway to 4.4 p.p. in Germany. Thus, again Germany shows the highest potential for reducing inefficiencies in the EU, followed by Poland and the UK. By introducing an ETS carbon price floor of 55€ in

¹¹The “rest of EU” comprises Luxembourg, Cyprus, Malta, Slovenia, Bulgaria, Romania, Croatia, Liechtenstein and Iceland.

2020, Germany is able to reduce overall EU emissions by 1.6% and national emissions by 9.1%. We also find that the retirement of emission allowances due to the carbon price floor in policy 2 would have little effects on the overall efficient price in which all sectors would be covered by the ETS. This price ranges from 41.9€, if Ireland and Norway would introduce an additional optimal tax, to 45.9€ for Germany, compared to 41.9€ in the benchmark situation. Yet, this comes at significant cost for those countries. In some cases (Poland and Italy) abatement costs are more than twice as high as in the BaU case.

	Policy 2							
	Carbon price floor in €	Efficient price in €	ΔI in p.p.	Δ cost in EU in %	Δ efficient cost in EU in %	Δ cost in country in %	EU-wide emission change in ETS in %	National emission change in ETS in %
Austria	52.3	42.0	-0.1	0.3	0.5	14.3	0.0	-3.1
Baltic states	52.3	43.3	-0.2	0.5	0.6	54.9	-0.1	-7.3
Belgium	52.3	42.2	-0.4	0.9	1.2	20.8	-0.1	-3.7
Czech Rep.	53.2	42.8	-1.1	2.8	3.7	63.2	-0.4	-14.6
Denmark	52.3	42.0	-0.2	0.4	0.5	12.5	-0.1	-3.3
Finland	52.3	42.2	-0.3	0.8	1.1	45.1	-0.1	-8.7
France	52.3	42.2	-0.4	1.0	1.3	12.6	-0.1	-1.3
Germany	55.0	45.9	-4.4	11.1	15.6	77.3	-1.6	-9.1
Greece	52.3	42.6	-0.9	2.1	2.8	25.0	-0.3	-5.2
Hungary	52.3	42.0	-0.1	0.3	0.4	47.3	-0.0	-4.0
Ireland	52.3	41.9	-0.1	0.1	0.2	21.5	-0.0	-2.1
Italy	53.2	42.8	-1.0	2.6	3.4	106.6	-0.3	-3.2
Netherlands	52.3	42.1	-0.3	0.7	1.0	8.7	-0.1	-2.3
Norway	52.3	41.9	-0.0	0.1	0.1	5.8	-0.0	-0.5
Poland	54.1	44.7	-3.1	8.0	10.8	108.0	-1.0	-13.1
Portugal	52.3	42.0	-0.2	0.4	0.6	46.4	-0.1	-4.2
Rest of EU	53.2	43.3	-1.6	4.1	5.4	43.5	-0.5	-9.2
Slovakia	52.3	42.1	-0.2	0.6	0.7	37.1	-0.1	-9.3
Spain	53.2	43.0	-1.2	3.1	4.1	41.8	-0.4	-5.1
Sweden	52.3	42.0	-0.1	0.2	0.3	8.6	-0.0	-2.1
UK	53.2	43.6	-2.0	4.7	6.6	51.1	-0.6	-4.6

Table 2: Policy simulation results for retiring emission allowances. In Benchmark: ETS price 27.4€, Efficient price 41.9€ and Inefficiency I 1.25.

3.3. Discussion

Our policy simulations for the EU carbon market show that there are possibilities for efficient additional national climate policy efforts. While policy 2 where allowances are retired is in principle already possible and goes in the direction of the German climate levy discussed in 2015, this is not the case for policy 1 where reduction targets are shifted from the ETS to the non-ETS sectors since the non-ETS targets are fixed in the EU effort sharing decision (European Commission, 2009). Our paper has shown though that such an option is advisable. Since it does not interfere with all EU targets but only increases the options for more ambitious countries it may be easier to agree on compared

to other reforms.

In any case, our empirical results have to be taken with care since our carbon pricing policy designs are very stylized. In practice, it would be very hard to monitor how much emissions may be shifted from the ETS to the non-ETS sector or retired due to the price floor. Moreover, there exist huge sectoral differences in abatement costs within the ETS and non-ETS sectors (recall Figure 3, Appendix C). Thus, potential efficiency gains very much depend on whether the additional tax is levied on coal-fired power plants in the electricity sector or on rubber production plants in the chemical sector. Policymakers may increase abatement targets in ETS sectors that face high marginal abatement costs but relax targets in non-ETS sectors that face low marginal abatement costs which may even result in efficiency losses. Analogously, regarding the efficiency analysis of policy 2 it also depends on which sectors are taxed and thus, how many emission allowances will be retired.

In order to put our results into context with current policy debates, we may compare our optimal carbon price floor levels with price floors that are currently discussed in certain EU countries even though most of them, with the exception of the German climate levy, do not include any shifting of targets (policy 1) or retirement of allowances (policy 2). Thus, they do not imply any emissions reductions and further increase inefficiencies as shown by Böhringer et al. (2008) and Heindl et al. (2014). It is important to note that - in its current design - this price floor as for instance announced in France (The Guardian, 2016) will further increase inefficiencies in the EU because it is simply an additional amount that certain emitters have to pay on top of the ETS allowance price. We find that it would increase EU ETS abatement costs by 1.1%. According to our policy scenarios, France has a much lower potential to reduce inefficiencies of the entire EU carbon market than other countries. Figure 4 shows the Inefficiency measure I depending on the national carbon price floor level for selected countries and both policies.

The horizontal line indicates the second best benchmark situation with 24.5% higher costs compared to a carbon market with all sectors included in the ETS ($I_{bmk} = 1.245$). The optimal carbon price floor level in France is 55.0€ (52.3€) for policy 1 (2). This price floor would lead to an EU-wide inefficiency reduction of 0.6 p.p. (0.4 p.p.). Hence, apart from the low inefficiency reduction potential, the announced price floor of 30€ in 2017 comes close to our estimates of France’s optimal price floor level if one also considers that the floor is supposed to gradually increase over time. It would at least not increase inefficiencies in the EU if combined with less emission reductions in the French non-ETS sector (policy 1) or with retiring allowances (policy 2). Moreover, France tries to convince Germany of jointly establishing a price floor in order to “create a momentum for other European countries” (Bloomberg, 2016a). A “simple” price floor of 30€ in Germany will increase EU ETS abatement costs by 9.5%. However, if allowing for our proposed policy options, the idea is promising since Germany shows the highest potential for reducing inefficiencies of the EU carbon market. Although, the optimal price floor level in Germany depends heavily on whether additional allowances are shifted to the non-ETS sectors (policy 1) or are simply retired (policy 2). The former policy should aim for price floor level of 36.3€ while the latter for 55.0€. Finally, we may compare

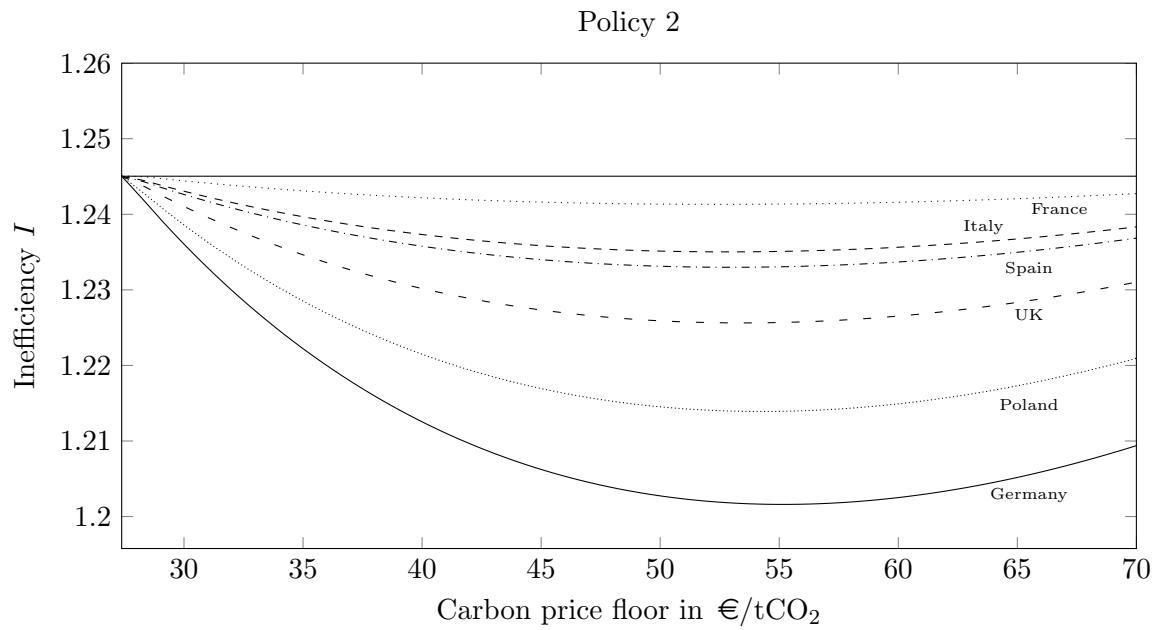
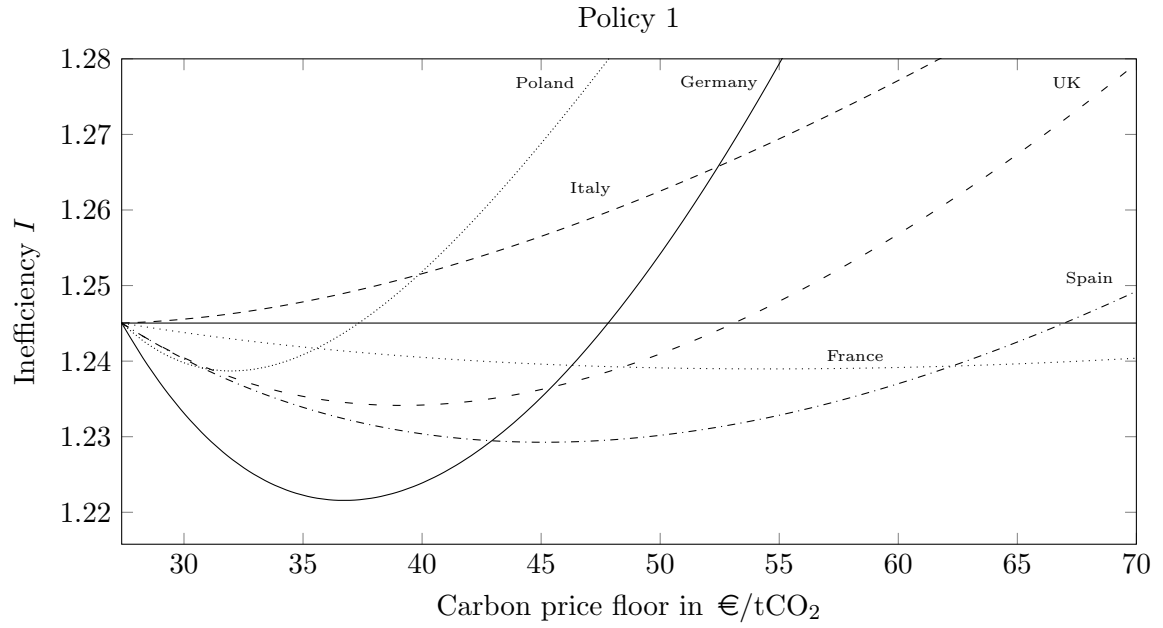


Figure 4: Change of cost inefficiencies in the EU due to the introduction of a national carbon price floor in the ETS sector.

our results with the UK price floor of 25€ which was introduced in 2013. We find that this price floor increases EU ETS abatement costs by 2.8%. Allowing for our alternative policy designs, we estimate an optimal price floor level of 39.0€ (53.2€) for policy 1 (2). This would lead to an EU-wide inefficiency reduction of 1.1 p.p. (2.0 p.p.). However, according to our estimates, as in France the current UK price floor does not lead to increasing inefficiencies in the EU climate policy framework in the context of our two policy cases.

All in all, we find that a national tax policy (or price floor) design in which emissions are simply retired and not shifted to the non-ETS sector has generally more potential to reduce overall inefficiencies in the EU carbon market. However, while shifting emission targets nationally implies that overall national costs are decreasing, the overall higher emission reductions implied by retiring allowances comes at some costs. Furthermore, Figure 4 shows that such a policy also increases the optimal price floor levels significantly compared to policy 1 implying also significantly higher costs for the national ETS sectors. Thus, policymakers will most likely face strong opposition from lobbies in these sectors.

4. Summary and Conclusion

In this paper, we explore the potential scope and optimal design of national climate policies in the current EU policy framework. The question is whether certain carbon pricing policies in the national EU ETS sectors, although interfering with the EU ETS, can be efficient and effective. While the type of policies for additional national climate policy efforts analyzed in previous papers are always found to be inefficient, we find that this need not be the case if national policies are designed in a way that allows for either shifting emissions from the ETS to non-ETS sectors or for retiring emission allowances. In a simple theoretical framework with two countries and two sectors, we show that these two policy options are efficient up to a certain carbon price threshold. Moreover, efficiency is the highest at an optimal carbon price level equaling a weighted sum of the price differentials between ETS and non-ETS sectors. Both, the threshold and optimal carbon price level are derived analytically.

In order to determine the empirical relevance for the EU, we conduct a numerical partial equilibrium analysis of the EU carbon market in 2020. The current inefficiency in the already second best benchmark situation with two separated carbon markets, one with emissions trading and one without, leads to 25% higher costs compared to a market with all sectors included in the EU ETS. We find that Germany has the highest potential to reduce EU-wide inefficiencies by introducing a carbon price floor. If shifting emissions from the ETS to non-ETS sector, Germany is able to reduce overall inefficiencies by 2.4% when introducing a price floor of 36.3€ in their EU ETS sector in 2020. At the same time German abatement costs are reduced by 12.6%. If Germany retires emission allowances, it is able to reduce inefficiencies by 4.4% when introducing a price floor of 55.0€ in 2020 and to reduce overall EU emission by 1.6%. Yet, this increased national abatement costs by 77.3%. Despite the stylized nature of our two policies, we conclude that national climate policy efforts can indeed be efficient in the current EU policy setting. One

possibility within the current EU policy framework is to combine carbon price floors in national EU ETS sectors with the retirement of EU ETS allowances. This policy does not only increase the efficiency of overall EU policy in the sense that it reduces the cost differential to the least cost solution but also leads to additional emissions reductions. Naturally, this also comes at additional costs for the country undertaking this policy. Our other option, shifting mitigation efforts from the non-ETS to ETS sectors is not possible within the current framework but our paper suggests that making this option possible on EU level is advisable.

A. Derivations

1. The solution of the linear system of equations

$$\begin{aligned}
 p &= a_1 x_1 \\
 p &= b_1 y_1 \\
 p &= a_2 x_2 \\
 p &= b_2 y_2 \\
 z &= x_1 + y_1 + x_2 + y_2
 \end{aligned}$$

for unknowns x_1, y_1, x_2, y_2 and p depending on the exogenous parameters, which are the overall abatement quantity z and slope parameters a_1, b_1, a_2, b_2 of the marginal abatement cost curves, can be written as

$$\begin{aligned}
 p^* &= \frac{z a_1 a_2 b_1 b_2}{a_1 a_2 b_1 + a_1 a_2 b_2 + a_1 b_1 b_2 + a_2 b_1 b_2} \\
 x_1^* &= \frac{p^*}{a_1} \\
 x_2^* &= \frac{p^*}{a_2} \\
 y_1^* &= \frac{p^*}{b_1} \\
 y_2^* &= \frac{p^*}{b_2}.
 \end{aligned}$$

2. The efficient solution for the ETS sector with the linear system of equations

$$\begin{aligned}
 \rho &= a_1 x_1 \\
 \rho &= a_2 x_2 \\
 z_x &= x_1 + x_2
 \end{aligned}$$

for unknowns ρ, x_1 and x_2 , is

$$\begin{aligned}
 \rho &= \frac{z_x a_1 a_2}{a_1 + a_2} \\
 \tilde{x}_1 &= \frac{z_x a_2}{a_1 + a_2} \\
 \tilde{x}_2 &= \frac{z_x a_1}{a_1 + a_2}.
 \end{aligned}$$

3. Derivation of inequality condition (15). For ease of notation, we neglect country

index i and the tilde. Further, we use y instead of z_y .

$$\begin{aligned}
\Delta &< 0? \\
\Delta &= \int_x^{x+\delta} ax \, dx + \int_y^{y-\delta} by \, dy \\
&= \frac{1}{2}a[(x+\delta)^2 - x^2] + \frac{1}{2}b[(y-\delta)^2 - y^2] \\
2\Delta &= a(x^2 + 2x\delta + \delta^2 - x^2) + b(y^2 - 2y\delta + \delta^2 - y^2) \\
&= a(\delta^2 + 2x\delta) + b(\delta^2 - 2y\delta) \\
&= \underbrace{(a+b)\delta^2}_{>0} + \underbrace{2\delta(ax - by)}_{>0} < 0? \\
\Rightarrow (a+b)\delta^2 &< -2\delta \underbrace{(ax - by)}_{< 0} \\
\Rightarrow (a+b)\delta^2 &< 2\delta \underbrace{(by - ax)}_{\pi - p} \\
\delta(a+b) &< 2(\pi - p) \\
\delta &< \frac{2(\pi - p)}{a+b}
\end{aligned}$$

4. Derivation of optimal tax level (21):

$$\begin{aligned}
\frac{\partial \Delta}{\partial \tau} &= x + \frac{\tau}{a} - \frac{by}{a} + \frac{b}{a^2}\tau \stackrel{!}{=} 0 \\
\tau\left(\frac{1}{a} + \frac{b}{a^2}\right) &= \frac{by}{a} - x \\
\tau &= (by - ax)\frac{a}{a+b} = \frac{a(\pi - \rho)}{a+b}
\end{aligned}$$

5. Linear system of equations with new target \hat{z} and the resulting efficient price and quantities:

$$\begin{aligned}
p &= a_1\hat{x}_1 \\
p &= b_1\hat{y}_1 \\
p &= a_2\hat{x}_2 \\
p &= b_2\hat{y}_2 \\
\hat{z} &= z + \delta_1.
\end{aligned}$$

The solution leads to the efficient price and quantities

$$\begin{aligned}
\hat{p}_1^* &= \frac{(z + \delta_1)a_1a_2b_1b_2}{a_1a_2b_1 + a_1a_2b_2 + a_1b_1b_2 + a_2b_1b_2} \\
\hat{x}_1^* &= \frac{\hat{p}_1^*}{a_1} \\
\hat{x}_2^* &= \frac{\hat{p}_1^*}{a_2} \\
\hat{y}_1^* &= \frac{\hat{p}_1^*}{b_1} \\
\hat{y}_2^* &= \frac{\hat{p}_1^*}{b_2}.
\end{aligned}$$

6. Inserting the efficient ETS quantities \tilde{x}_1 and \tilde{x}_2 from A2 into

$$\frac{A_{bmk} + \Delta_{pol2}}{A_{bmk}} = 1 + \frac{a_1\delta_1^2 + 2a_1\tilde{x}_1\delta_1}{a_1\tilde{x}_1^2 + b_1z_{y_1}^2 + a_2\tilde{x}_2^2 + b_2z_{y_2}^2},$$

leads to

$$\begin{aligned}
\frac{A_{bmk} + \Delta_{pol2}}{A_{bmk}} &= 1 + \frac{a_1\delta_1^2 + 2a_1\tilde{x}_1\delta_1}{a_1\left(\frac{z_x a_2}{a_1 + a_2}\right)^2 + a_2\left(\frac{z_x a_1}{a_1 + a_2}\right)^2 + b_1z_{y_1}^2 + b_2z_{y_2}^2} \\
&= 1 + \frac{a_1\delta_1^2 + 2a_1\tilde{x}_1\delta_1}{\frac{a_1a_2z_x^2(a_2+a_1)}{(a_2+a_1)^2} + b_1z_{y_1}^2 + b_2z_{y_2}^2} \\
&= 1 + \frac{a_1\delta_1^2 + 2a_1\tilde{x}_1\delta_1}{\frac{a_1a_2z_x^2}{a_1+a_2} + b_1z_{y_1}^2 + b_2z_{y_2}^2}.
\end{aligned}$$

Finally, since in equilibrium $\rho = a_1\tilde{x}_1$ and $\pi_i = b_iz_{y_i}$, we obtain

$$\frac{A_{bmk} + \Delta_{pol2}}{A_{bmk}} = 1 + \frac{a_1\delta_1^2 + 2\rho\delta_1}{\rho z_x + \pi_1 z_{y_1} + \pi_2 z_{y_2}}.$$

7. By inserting efficient quantities of A.1 and A.5, we obtain for the right hand side in the last line of (23)

$$\begin{aligned}
\frac{K_{bmk} + \Theta}{K_{bmk}} &= \frac{\frac{1}{2}a_1 \left(\frac{(z+\delta_1)a_2b_1b_2}{\gamma} \right)^2 + \frac{1}{2}b_1 \left(\frac{(z+\delta_1)a_1a_2b_2}{\gamma} \right)^2 + \frac{1}{2}a_2 \left(\frac{(z+\delta_1)a_1b_1b_2}{\gamma} \right)^2 + \frac{1}{2}b_2 \left(\frac{(z+\delta_1)a_1a_2b_1}{\gamma} \right)^2}{\frac{1}{2}a_1 \left(\frac{za_2b_1b_2}{\gamma} \right)^2 + \frac{1}{2}b_1 \left(\frac{za_1a_2b_2}{\gamma} \right)^2 + \frac{1}{2}a_2 \left(\frac{za_1b_1b_2}{\gamma} \right)^2 + \frac{1}{2}b_2 \left(\frac{za_1a_2b_1}{\gamma} \right)^2} \\
&= \frac{\frac{(z+\delta_1)^2}{\gamma^2}}{\frac{z^2}{\gamma^2}} \frac{\frac{1}{2}a_1 \left(\frac{a_2b_1b_2}{\gamma} \right)^2 + \frac{1}{2}b_1 \left(\frac{a_1a_2b_2}{\gamma} \right)^2 + \frac{1}{2}a_2 \left(\frac{a_1b_1b_2}{\gamma} \right)^2 + \frac{1}{2}b_2 \left(\frac{a_1a_2b_1}{\gamma} \right)^2}{\frac{1}{2}a_1 \left(\frac{a_2b_1b_2}{\gamma} \right)^2 + \frac{1}{2}b_1 \left(\frac{a_1a_2b_2}{\gamma} \right)^2 + \frac{1}{2}a_2 \left(\frac{a_1b_1b_2}{\gamma} \right)^2 + \frac{1}{2}b_2 \left(\frac{a_1a_2b_1}{\gamma} \right)^2} \\
&= \frac{(z + \delta_1)^2}{z^2}.
\end{aligned}$$

8. Solving the inequality (24):

$$\begin{aligned}
\frac{(z + \delta_1)^2}{z^2} &> 1 + \frac{a_1\delta_1^2 + 2\rho\delta_1}{\rho z_x + \pi_1 z_{y_1} + \pi_2 z_{y_2}} \\
\Leftrightarrow \frac{(z + \delta_1)^2}{z^2} - \frac{a_1\delta_1^2 + 2\rho\delta_1}{Q} &> 1 \\
\Leftrightarrow (z + \delta_1)^2 - (a_1\delta_1^2 + 2\rho\delta_1) \frac{z^2}{Q} &> z^2 \\
\Leftrightarrow (z^2 + 2z\delta_1 + \delta_1^2) - (a_1\delta_1^2 + 2\rho\delta_1) \frac{z^2}{Q} &> z^2 \\
\Leftrightarrow (2z\delta_1 + \delta_1^2) - (a_1\delta_1^2 + 2\rho\delta_1) \frac{z^2}{Q} &> 0 \\
\Leftrightarrow \delta_1^2 \left(1 - a_1 \frac{z^2}{Q}\right) + 2\delta_1 \left(z - \rho \frac{z^2}{Q}\right) &> 0 \\
\Leftrightarrow \delta_1 \left(1 - a_1 \frac{z^2}{Q}\right) + 2 \left(z - \rho \frac{z^2}{Q}\right) &> 0 \\
\Leftrightarrow \delta_1 &< -\frac{2(z - \rho \frac{z^2}{Q})}{(1 - a_1 \frac{z^2}{Q})} \\
\Leftrightarrow \delta_1 &< \frac{2(\rho \frac{z^2}{Q} - z)}{(1 - a_1 \frac{z^2}{Q})} \\
\Leftrightarrow \delta_1 &< \frac{2Qz - 2\rho z^2}{a_1 z^2 - Q}
\end{aligned}$$

B. Tables

Data: Regarding the ETS sectors, we use historic emissions from 2008 to 2012 of the European Environment Agency (2016) while from 2013 to 2020 applying a reduction of 1.74% p.a. for each EU region as envisaged by phase 3 of the EU ETS.¹² The resulting reduction factors for the ETS sectors in 2020 compared to 2007 emissions range from 0.45 for the Czech Republic to 1.46 for Sweden. Regarding the non-ETS sectors, national emission targets are given by the Effort Sharing Decision of the European Commission (2013), implying a reduction of 1.95% p.a. from 2013 to 2020 for each EU member country. This results in an emissions reduction factor of 0.87 for each region in 2020.

	EU carbon market data in 2020							
	Emissions in 2007 (Mt CO ₂)		Yearly reduction rate from 2013-2020 (in %)		Emission target in 2020 (Mt CO ₂)		Reduction factor in 2020 to 2007 emissions	
	ETS	n-ETS	ETS	n-ETS	ETS	n-ETS	ETS	n-ETS
Austria	33	57			32	49	0.99	
Baltic States	36	22			22	19	0.62	
Belgium	60	80			59	70	0.97	
Czech Rep.	97	53			44	46	0.45	
Denmark	28	44			22	38	0.79	
Finland	45	36			37	32	0.83	
France	150	400			100	349	0.67	
Germany	497	498			418	434	0.84	
Greece	71	67	↑	↑	46	58	0.64	↑
Hungary	31	43			19	37	0.6	
Ireland	19	53	1.74	1.95	14	46	0.73	0.87
Italy	203	368			165	321	0.81	
Netherlands	86	133	↓	↓	74	116	0.86	↓
Norway	18	0			19	0	1.03	
Poland	238	175			114	152	0.48	
Portugal	37	46			27	40	0.73	
Rest of EU	134	168			128	146	0.96	
Slovakia	30	19			29	17	0.94	
Spain	160	294			137	256	0.86	
Sweden	23	45			33	39	1.46	
UK	216	497			153	433	0.71	
EU-28 total	2213	3097	1.74	1.95	1692	2699	0.76	0.87

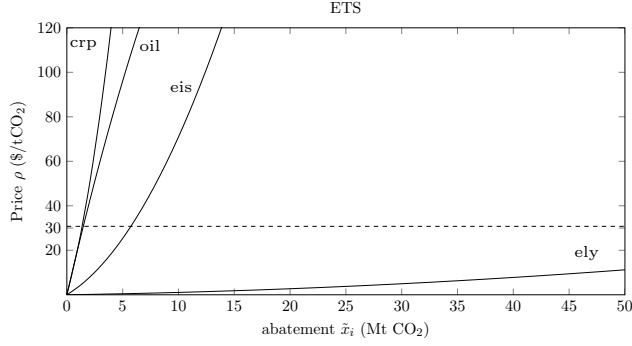
Table 3: EU emission targets and resulting reduction factors for 21 regions in the year 2020.

¹²See European Commission (2016). Although 1.74% p.a. is the reduction of the single EU-wide cap, we may apply it as a regional reduction rate within the model.

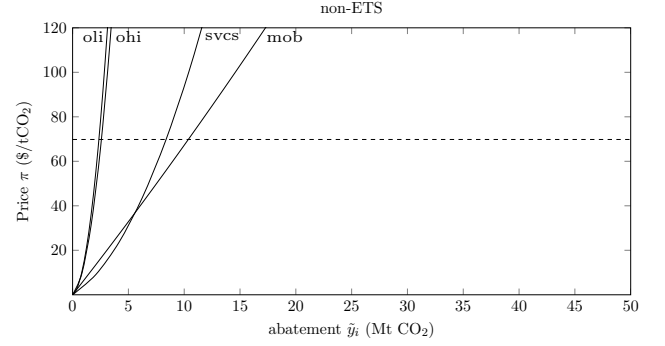
	ETS		n-ETS	
	\hat{a}	\hat{b}	\hat{c}	\hat{d}
Austria	1.65*** (0.02)	6.80*** (0.10)	0.37*** (0.00)	7.29*** (0.08)
Baltic states	1.01*** (0.00)	-2.11*** (0.18)	1.35*** (0.02)	12.53*** (0.13)
Belgium	0.29*** (0.00)	0.70*** (0.02)	0.16*** (0.00)	4.90*** (0.06)
Czech Rep.	0.03*** (0.04)	-0.07 (0.05)	0.51*** (0.00)	1.91*** (0.06)
Denmark	1.42*** (0.00)	-1.76*** (0.30)	0.41*** (0.01)	7.77*** (0.13)
Finland	0.36*** (0.01)	0.12* (0.06)	1.42*** (0.03)	21.91*** (0.22)
France	0.25*** (0.00)	0.34** (0.10)	0.01*** (0.00)	1.22*** (0.01)
Germany	0.00*** (0.00)	0.10*** (0.00)	0.01*** (0.00)	0.85*** (0.02)
Greece	0.05*** (0.03)	0.30*** (0.06)	0.01*** (0.00)	0.71*** (0.01)
Hungary	1.97*** (0.00)	5.32*** (0.13)	1.01*** (0.01)	8.28*** (0.10)
Ireland	7.87*** (0.00)	-3.76*** (0.17)	0.66*** (0.01)	8.69*** (0.10)
Italy	0.04*** (0.38)	0.18*** (0.03)	0.01*** (0.00)	2.28*** (0.03)
Netherlands	0.42*** (0.96)	0.53*** (0.14)	0.07*** (0.00)	3.05*** (0.04)
Norway	48.02*** (0.06)	-1.44 (1.07)	0.42*** (0.00)	7.95*** (0.07)
Poland	0.00*** (0.01)	0.17*** (0.01)	0.07*** (0.00)	-0.10 (0.06)
Portugal	1.24*** (0.03)	-1.81*** (0.20)	0.56*** (0.02)	14.63*** (0.17)
Rest of EU	0.01*** (0.01)	0.26*** (0.02)	0.07*** (0.00)	2.35*** (0.03)
Slovakia	0.77*** (0.00)	-0.62*** (0.12)	3.12*** (0.04)	1.17*** (0.28)
Spain	0.03*** (0.00)	-0.40*** (0.03)	0.02*** (0.00)	2.12*** (0.03)
Sweden	6.11*** (0.02)	7.01*** (1.01)	0.65*** (0.01)	15.40*** (0.10)
United Kingdom	0.01*** (0.00)	0.14*** (0.02)	0.01*** (0.00)	0.45*** (0.03)

Table 4: Estimation results of MAC curve slope parameters. Significance levels: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Standard errors in parantheses.

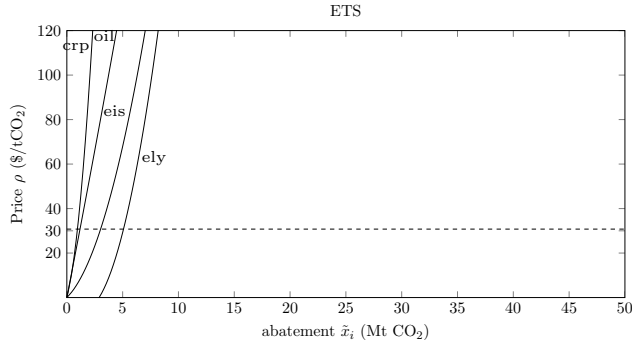
C. Figures



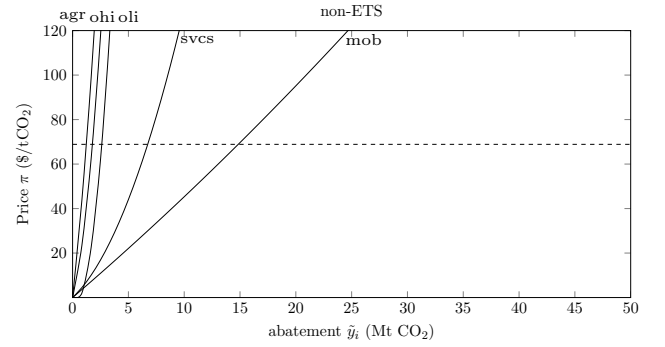
(a) Germany's sectoral MAC curves in ETS



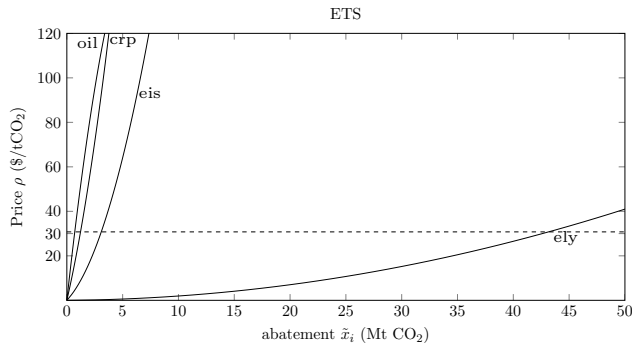
(b) Germany's sectoral MAC curves in non-ETS



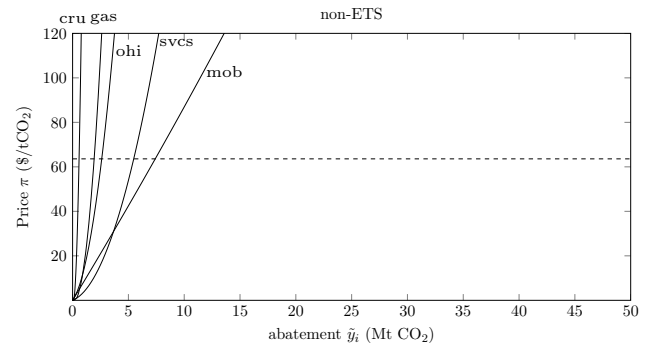
(c) France's sectoral MAC curves in ETS



(d) France's sectoral MAC curves in non-ETS



(e) UK's sectoral MAC curves in ETS



(f) UK's sectoral MAC curves in non-ETS

Figure 5: Sectoral MAC curves in selected ETS and non-ETS sectors of Germany, France and the UK.

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