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Johannes Burmeister, Sonja Peterson

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ABSTRACT

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Given that the carbon price in the EU Emissions Trading System (ETS) is only around 5€/tCO_2 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 allows for shifting emissions to non-ETS sectors like housing and transportation and retiring EU-wide emission allowances. In a simple theoretical framework with two countries and two sectors, we derive the optimality conditions for three different carbon price floor policy designs. Moreover, we are able to derive a closed form solution for the optimal price floor levels of each policy. 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 cost inefficiencies and emission levels. Depending on the policy objective, Germany is able to reduce EU-wide abatement costs by 2.1% or emissions by 0.1% with a floor of 37€/tCO_2 and 33€/tCO_2, respectively. Finally, we find that the German climate levy proposal for old coal power plants from 2015 would have been a highly costly price floor option while its cost efficiency results are very unclear.

Keywords: Climate policy, EU Emission Trading System, Overlapping regulation, Carbon price floors, Abatement costs
JEL classification: Q58, H21, H23, D58

Johannes Burmeister
Kiel Institute for the World Economy
Kiellinie 66
D-24105 Kiel
Germany
Email: johannes.burmeister@ifw-kiel.de

Sonja Peterson
Kiel Institute for the World Economy
Kiellinie 66
D-24105 Kiel
Germany
Email: sonja.peterson@ifw-kiel.de

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Johannes Burmeister* & Sonja Peterson†

March 9, 2017

Abstract

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*Corresponding author. Kiel Institute for the World Economy, Kiellinie 66, 24105 Kiel, Germany. Email: Johannes.Burmeister@ifw-kiel.de
†Kiel Institute for the World Economy, Kiellinie 66, 24105 Kiel, Germany. Email: Sonja.Peterson@ifw-kiel.de

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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 minimum costs.

A cornerstone of EU climate policy 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 in principle ensures efficiency because due to emissions trading marginal abatement costs (MAC) across sources equalize and thereby the exogenous overall emissions target (the so-called cap) is reached at minimum costs.

Yet, the system produces large inefficiencies since the EU ETS only covers about half of EU GHG emissions. 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 resulting inefficiencies 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.[1] 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 €/tCO_2 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 target stressed in the Paris Agreement from 2015 (United Nations, 2016). Yet, every reform of the current EU

[1] In reality, inefficiencies are potentially 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 models used in Böhringer et al. (2009).

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 (e.g. in Sweden, Finland and Denmark) for sectors already covered by the EU ETS. In 2016, also France announced the introduction of a 30 €/tCO_2 carbon price floor in the electricity sector in 2017 (The Guardian, 2016). Germany discussed an additional "climate levy" for old coal power plants (BMWi, 2015) as well as a general carbon price floor (Bloomberg, 2016b). The former stipulated that old coal fire plants have to submit a certain amount of additional allowances on top of the EU allowances for emissions beyond a certain emission level. These additional allowances are then retired by the government. Due to this design, the proposal 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 three new policy designs. These account for the possibility to shift emission allowances between ETS and non-ETS sectors and to 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 adds alternative carbon pricing policy designs thereby contradicting previous efficiency results. The general idea to allow for the adjustment of emission targets in either the ETS or non-ETS sector as motivated above is similar as in Abrell and Rausch (2016b). But while Abrell and Rausch (2016b) take the perspective of a social planner for the EU that aims to shift emissions from the EU ETS to all non-ETS sectors to minimize overall EU inefficiencies (which would again require unanimous approval by all member states), we take a national perspective. Our paper 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 emissions trading scheme (e.g. Weitzman, 1974; Roberts and Spence, 1976; Unold and Requate, 2001; Mandell, 2008; Wood and Jotzo, 2011; Abrell and Rausch, 2016a; Brink et al., 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 three policy options 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 in order to evaluate the environmental effectiveness and cost efficiency of additional national climate policies in the EU 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).

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 CO_2 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 in the ETS sector are grandfathered. Thus, both countries have a joint emissions abatement target

$$z_x = x_1^T + x_2^T \tag{1}$$

in the ETS sector with ex-ante abatement quantities x_1^T and x_2^T.[2] Within the joint target z_x, countries i can trade emission allowances as needed because their actual abatement

[2] Note 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 (bau) emissions, then $x_i^T := e_i^0 - e_i$.

x_i may be either greater or less than ex-ante allocated quantities x_i^T depending on their abatement possibilities. 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 first order conditions that marginal abatement costs equalize across the two countries, i.e.

$$\rho = c_1'(\tilde{x}_1) = c_2'(\tilde{x}_2), \tag{2}$$

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

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

whereas a positive sign denotes exports and a negative imports.

Regarding the non-ETS sector, there does not exist a joint abatement target but only national targets z_{y_1} and z_{y_2} for each country. For simplicity, we follow Böhringer et al. (2016, p. 505) and assume that these single targets are met by national carbon taxes

$$\pi_1 = c_1'(\tilde{y}_1) \tag{4}$$

and

$$\pi_2 = c_2'(\tilde{y}_2), \tag{5}$$

such that

$$z_{y_1} = \tilde{y}_1 \tag{6}$$

and

$$z_{y_2} = \tilde{y}_2. \tag{7}$$

Therefore, the overall abatement target across all countries and sectors

$$z = z_x + z_{y_1} + z_{y_2} = \tilde{x}_1 + \tilde{x}_2 + \tilde{y}_1 + \tilde{y}_2. \tag{8}$$

is reached by a second best solution with three potentially different carbon prices ρ, π_1 and π_2. The latter two can be regarded as the level of national carbon taxes in order to achieve the non-ETS target. We call this second best solution the benchmark situation as it reflects, in a simplified manner, the current EU carbon market situation.[3] The general setting is summarized in Figure 1 where the functional form of the MAC curves is chosen arbitrarily. 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 typically left to the ETS ones.

[3] Of course, while in the EU market there also exist only one ETS price, there exist many potentially different (shadow) prices outside the ETS in the 28 member states and their various non-ETS sectors.

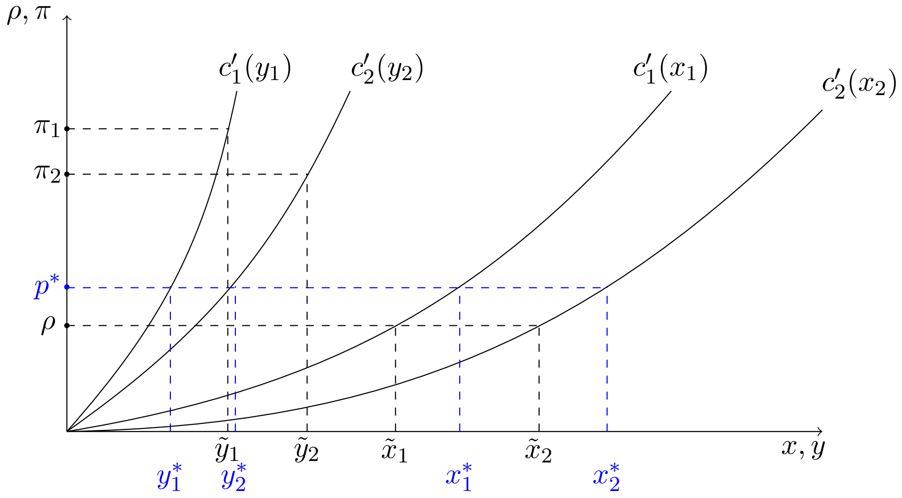


Figure 1: MAC curves for the two country and two sector model.

The first best cost-efficient solution implies that marginal abatement costs equalize across *both* sectors and countries. Thus, first-order conditions are

$$p^* = c_1'(x_1^*) = c_1'(y_1^*) = c_2'(x_2^*) = c_2'(y_2^*), \tag{9}$$

with optimal abatement quantities x_1^*, x_2^*, y_1^* and y_2^*. p^* denotes the optimal value of the marginal abatement cost or allowance price. 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 guaranteed if all sectors are covered by the emissions trading scheme of the ETS sector.

Let $C(\tilde{x}_i, \tilde{y}_i, z)$ denote the total abatement costs of all countries and sectors in the second best benchmark solution with overall abatement target z and $C(x_i^*, y_i^*, z)$ total costs of the first best efficient solution. We then define an inefficiency measure

$$I_{bmk} := \frac{C(\tilde{x}_i, \tilde{y}_i, z)}{C(x_i^*, y_i^*, z)} \tag{10}$$

in the benchmark situation as the cost-markup factor (≥ 1) of the separated carbon market. We now turn to our three policy cases and evaluate their environmental effectiveness and cost-efficiency.

2.1. Policy 1 - Minimizing national abatement costs while keeping abatement constant

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 in country 2 i.e. to a counter-effect and overall unchanged ETS emissions since the ETS target remains the same. However, in policy case 1, we assume that the government which introduces the policy uses the tax (or fee) revenue in order to buy these excess allowances and to retire them. This also means that country 2 is not affected by the national policy in country 1. 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, the overall abatement target is held fix so that policy 1 is environmentally not effective but policymakers aim to optimize national abatement costs by shifting emissions from the ETS to non-ETS sector. The optimization problem is given by

$$\begin{aligned} \min \quad C_1(\tilde{x}_1, \tilde{y}_1, \delta_1, z) = & \quad c_1(\tilde{x}_1 + \delta_1) + c_1(\tilde{y}_1 - \delta_1) \\ \text{s.t.} \quad z = & \quad \tilde{x}_1 + \tilde{x}_2 + \tilde{y}_1 + \tilde{y}_2, \end{aligned} \tag{11}$$

where C_1 are total abatement costs in country 1 and δ_1 is the additional abatement effort in the ETS sector. Solving (11) leads to the first order condition

$$\frac{\partial C_1(\tilde{x}_1, \tilde{y}_1, \delta_1, z)}{\partial \delta_1} \stackrel{!}{=} 0 \Rightarrow \frac{\partial c_1(\tilde{x}_1 + \delta_1)}{\partial \delta_1} \stackrel{!}{=} \frac{\partial c_1(\tilde{y}_1 - \delta_1)}{\partial \delta_1}. \tag{12}$$

In words, the optimal tax level τ_1^* of policy 1 equalizes marginal abatement costs of the ETS and non-ETS sector in country 1. This is also shown in Figure 2 below where the functional form of MAC curves is again chosen arbitrarily. The dark gray shaded area are the additional costs in the ETS sector and the light gray shaded are the reduced costs in the non-ETS sector. The difference i.e. cost-efficiency is the highest at the optimal tax level that equalizes marginal abatement costs of both sectors. The inefficiency measure of policy 1

$$I_{pol1} = \frac{C(\tilde{x}_i, \tilde{y}_i, \delta_1, z)}{C(x_i^*, y_i^*, z)}$$

is lower compared to the benchmark situation given by (10) since total inefficient abatement costs decrease (the numerator) while total efficient costs remain the same (the denominator). Thus, policy 1 is environmentally not effective but improves national and also overall cost-efficiency of the carbon market.

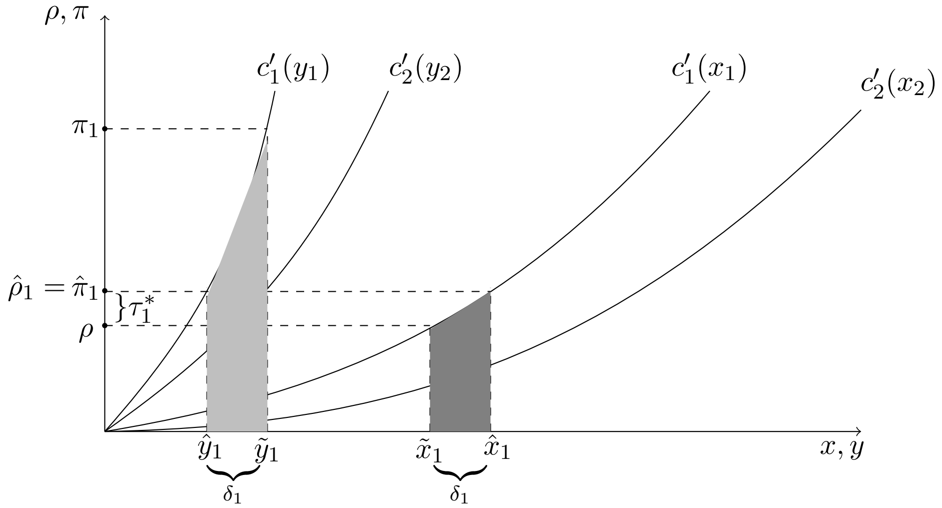


Figure 2: Effectiveness and efficiency of the first policy case.

Assuming simple linear MAC curves, it is possible to derive a closed form solution of the optimal tax level that can also be easily interpreted. The optimal tax level of policy 1 is given by

$$\tau^*_{1,pol1} = \frac{a_1(\pi_1 - \rho)}{a_1 + b_1}, \tag{13}$$

(see Appendix A.1). a_1 and b_1 are the slope parameters of the linear MAC curves of the ETS and non-ETS sector, respectively. Thus, the optimal tax level is a weighted price differential between the non-ETS and ETS sector of country 1.

2.2. Policy 2 - Maximizing national abatement while keeping abatement costs constant

In the second policy case, country 1 is again eager to increase abatement efforts by introducing a carbon tax in the ETS sector and to relax abatement in the non-ETS sector. Analogously to policy 1, the government buys the excess emission allowances and retires them so that country 2 is unaffected by the national policy measure in country 1. However, this time policymakers aim to maximize the environmental effectiveness while holding national abatement costs constant. Formally, the optimization problem of the second policy case is given by

$$\begin{aligned} \max \quad U_1 &= \delta_1 - \mu_1 \\ \text{s.t.} \quad c_1(\tilde{x}_1 + \delta_1) + c_1(\tilde{y}_1 - \mu_1) &= c_1(\tilde{x}_1) + c_1(\tilde{y}_1). \end{aligned}$$

U_1 denotes the environmental surplus as the difference between additional abatement in the ETS sector δ_1 and reduced abatement in the non-ETS sector μ_1. Setting up the Lagrangian function $L(\delta_1, \mu_1, \lambda)$ and differentiating with respect to δ_1, μ_1 and the

Lagrange multiplier λ, leads to the first order conditions of policy 2

$$\frac{\partial L(\delta_1, \mu_1, \lambda)}{\partial \delta_1} = 1 + \lambda \frac{\partial c(\tilde{x}_1 + \delta_1)}{\partial \delta_1} \stackrel{!}{=} 0, \tag{14}$$

$$\frac{\partial L(\delta_1, \mu_1, \lambda)}{\partial \mu 1} = 1 + \lambda \frac{\partial c(\tilde{y}_1 - \mu_1)}{\partial \mu_1} \stackrel{!}{=} 0 \tag{15}$$

and

$$c(\tilde{x}_1 + \delta_1) + c(\tilde{y}_1 - \mu_1) - c(\tilde{x}_1) - c(\tilde{y}_1) \stackrel{!}{=} 0. \tag{16}$$

Solving the system of equations (14)-(16) for the unknowns δ_1 and μ_1 would lead to the analytical solution of the optimal additional abatement levels δ_1^* and μ_1^*. Given δ_1^*, it is possible to derive the optimal tax rate τ_1^* of policy 2 as shown in Figure 3. The difference between the new abatement level in the ETS sector $\hat{x}_1$ and the old level $\tilde{x}_1$ can be translated into the difference between the new ETS price $\hat{\rho}_1$ and the old price ρ i.e. the optimal tax level τ_1^*. The additional costs in the ETS sector (dark shaded) equals the reduced costs in the non-ETS sector (light shaded) while overall abatement increases.

Assuming simple linear MAC curves as in policy 1, it is also possible to derive a closed form solution of the optimal tax level which is again a weighted price differential between sectors. However, compared to policy 1 the solution cannot be easily interpreted (see Appendix A.2).

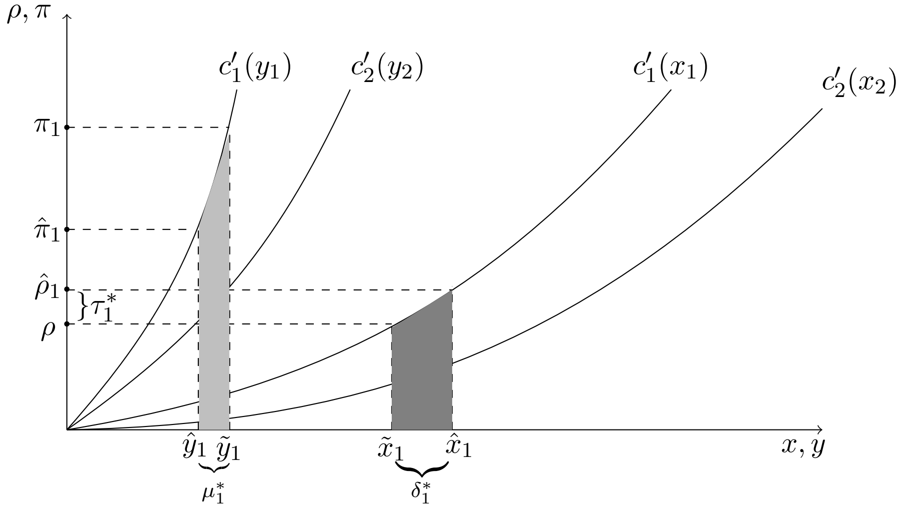


Figure 3: Effectiveness and efficiency of the second policy case.

As in the case of policy 1, the inefficiency measure of policy 2

$$I_{pol2} = \frac{C(\tilde{x}_i, \tilde{y}_i, \delta_1, \mu_1, \hat{z})}{C(x_i^*, y_i^*, \hat{z})} \tag{17}$$

is lower compared to the benchmark situation given by (10) since total inefficient abatement costs remain unchanged (the numerator) while total efficient costs increase (the denominator) due to the increased overall target

$$\hat{z} = \tilde{x}_1 + \delta_1 + \tilde{x}_2 + \tilde{y}_1 - \mu_1 + \tilde{y}_2.$$

Thus, policy 2 is environmentally effective *and* improves cost-efficiency of the carbon market.

2.3. Policy 3 - Minimizing inefficiencies

In the third policy case, we revisit the German climate levy proposal for inefficient coal-fired power plants. The proposal stipulated that such power plants need to buy additional ETS allowances and sign them over to the government which in turn retires the allowances. If translated into our simple theoretical framework, country 1 again increases its abatement effort in the ETS sector by an additional tax (or levy or additional allowances). However, this time no adjustment of the abatement efforts in the non-ETS sector takes place. The government simply buys the excess allowances of the ETS sector and retires them. Hence, in contrast to policy 1 and 2, neither abatement costs are minimized nor environmental effectiveness is maximized. On the one hand, the additional abatement effort without shifting but retiring emissions makes the policy environmentally effective. On the other hand, the additional abatement effort increases costs. Thus, policymakers do not directly follow an optimization behaviour. More technically, both the nominator and denominator of inefficiency measure I in (10) change. Since we are not able to directly measure the benefits of the environmental effectiveness, policy 3 cannot be easily compared with the benchmark situation because both the costs as well as revenues of the national policy change. The question is therefore, what is a sensible optimization behaviour for this policy? One policy target that makes sense could be to minimize the inefficiencies of the system with separated carbon markets compared to an overall efficient solution. This would imply to minimize our inefficiency measure I_{pol3}, i.e.

$$\min \quad I_{pol3} \quad = \quad \frac{C(\tilde{x}_i, \tilde{y}_i, \delta_1, \bar{z})}{C(x_i^*, y_i^*, \bar{z})}, \tag{18}$$

with increased overall abatement target

$$\bar{z} = \tilde{x}_1 + \delta_1 + \tilde{x}_2 + \tilde{y}_1 + \tilde{y}_2.$$

Solving (18) leads to the first order condition of policy 3

$$\frac{\partial I_{pol3}}{\partial \delta_1} = \frac{\frac{\partial C(\tilde{x}_i, \tilde{y}_i, \delta_1, \bar{z})}{\partial \delta_1}}{\frac{\partial C(x_i^*, y_i^*, \bar{z})}{\partial \delta_1}} \stackrel{!}{=} 0. \tag{19}$$

Assuming simple linear MAC curves, it is again possible to derive a closed form solution of the optimal tax level as for policy 1 (and 2). It is given by

$$\tau^*_{1,pol3} = \frac{a_1(\frac{Q}{z} - \rho)}{a_1 - \frac{\rho}{z}}, \tag{20}$$

with target weighted price index

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

(see Appendix A.3). Thus, similar to the analytical solution of policy 1, the optimal tax level is a weighted price differential between the sectors. However, in contrast to policy 1, the optimal tax of policy 3 also depends on prices and targets of country 2. The nominator of (20) is a price differential between the sum of all prices weighted by their respective as well as overall target and the ETS price. The denominator is the difference between the slope parameter of the ETS MAC curve in country 1 and an artificial slope parameter ρ/z.

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 minimizes national abatement costs (policy 1), maximizes national abatement while leaving costs unaffected (policy 2) and mimics the German climate levy proposal (policy 3). In all three policy cases, the government buys the excess emission allowances and retires them. However, the former two policies allow for shifting emissions from the ETS to the non-ETS sector while the latter does not.

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 CO_2 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 4, Appendix B).[4] 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 CO_2 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 bau fashion over time. In this case, there is no price for emitting CO_2. However, if a quantity target is exogenously set, the model returns an implicit (shadow) price for CO_2 emissions due to the constraint. By simultaneously varying this quantity constraint for the EU regions in ETS and non-ETS sectors, we generate a sequence of CO_2 price and abatement quantity combinations in 2020.[5] The resulting MAC curves for selected EU regions and relative abatement in both the aggregated ETS and non-ETS sector are shown in Figure 4. We assume non-linear MAC curves of the form

$$\rho = c_i'(x_i) = a_i x_i^3 + b_i x_i^2 + c_i x_i + d_i \tag{21}$$

and

$$\pi_i = c_i'(y_i) = e_i y_i^3 + f_i y_i^2 + g_i y_i + h_i \tag{22}$$

for $i = 1, ..., 21$ EU regions. Inserting the equilibrium abatement quantities $\tilde{x}_i$ and $\tilde{y}_i$ and respective CO_2 prices ρ and π_i in (21) and (22), we fit the MAC curves in Figure 4 by least-squares to obtain estimates for the slope parameters $\hat{a}_i$ to $\hat{h}_i$. The fit of the OLS regression is shown in Figure 6, Appendix C where the dotted curves are absolute abatement levels obtained from the CGE model and the solid curves are the respective OLS fits.[6]

[4] For 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.

[5] For 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.

[6] Please note that the intercept with the y-axis especially in the non-ETS sector stem from energy market effects as described in Klepper and Peterson (2006).

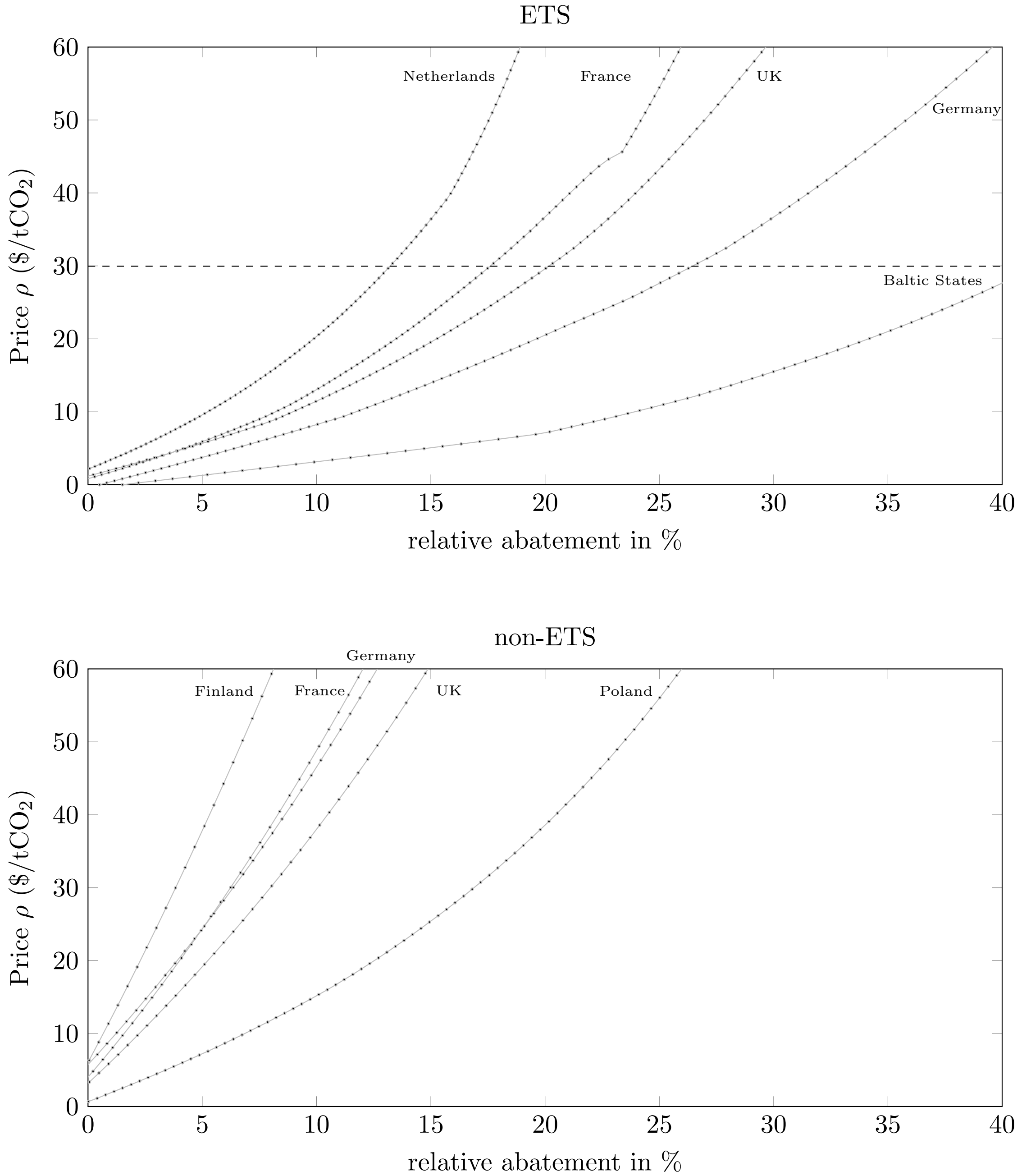


Figure 4: MAC curves of the ETS and non-ETS sectors in selected countries.

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 shown in Figure 4. Abatement in the ETS sectors is the cheapest in the Baltic States and most expensive in the Netherlands whereas abatement in the non-ETS sectors is the cheapest in Poland and most expensive in Finland. Moreover, marginal abatement costs also differ across the different ETS and non-ETS sectors. Figure 7, 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. 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, the coal mining sector shows the cheapest abatement possibilities in Germany and the UK. In France, it is the cheapest to abate emissions in the natural gas extraction sector. For all three countries, it is the most expensive to abate emissions in the mobility sector.

3.2. 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 bau emissions less the emission targets then lead to abatement targets in 2020 with respective CO_2 prices. Table 4 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 z_{y_i} are exogenous and assumed to be met by national carbon taxes, i.e.

$$\begin{aligned} \min_{x_i, y_i} \quad & \sum_i \quad c(x_i) + c(y_i) \\ \text{s.t.} \quad & \sum_i \quad x_i = z_x \qquad \wedge \quad y_i = z_{y_i} \quad \forall i. \end{aligned} \tag{23}$$

The resulting benchmark price ρ for the EU ETS in 2020 is around 27€/tCO_2 (see dashed line in Figure 4).[7] 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 28€ in Italy up to 119€ in the Netherlands (see first column of Table 1). In order to evaluate the

[7]Since the GTAP data is in dollars, we convert prices with the exchange rate 1\$=0.89€. In the following, we skip the "€/tCO_2" dimension.

inefficiency of the EU carbon market I_{bmk} given by (10), we include the non-ETS sector in the cap-and-trade system and solve the model again for the overall efficient solution

$$\min_{x_i, y_i} \sum_i c(x_i) + c(y_i) \quad \text{s.t.} \quad \sum_i (x_i + y_i) = z. \tag{24}$$

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 three 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 1-3, 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 minimizes its abatement costs by shifting emissions from the ETS to non-ETS sector, the only country where any carbon price floor is inefficient and increases costs is Italy. In all other countries, the optimal carbon price floor[8] is positive and varies between 31 € in Poland and 85 € in the Netherlands, shifting up to a quarter of national ETS emissions to the non ETS sector, where the target thus increases by up to 20%. National cost reductions of these floor prices can be significant and savings are as high as 20-30% in almost half of the countries. In only a third of the countries the savings are less than 10%. Thus, policy 1 is very attractive from a national perspective. The resulting EU-wide cost reductions are much smaller and range from 0.04% in Hungary and Ireland to 2.6% in the "rest of EU" region[9]. Except for the "rest of EU", Germany shows the highest potential for reducing costs of the EU carbon market, followed by the Netherlands and Spain. By introducing a carbon price floor of 37 € in 2020, Germany is able to reduce overall EU costs by 2.1%. 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 1.1%. However, note that the absolute emission level in the EU remains constant in this setting.

[8]The optimal ETS carbon price floor is the old EU-wide ETS price of 26.7 € plus the additional optimal tax.

[9]The "rest of EU" comprises Luxembourg, Cyprus, Malta, Slovenia, Bulgaria, Romania, Croatia, Liechtenstein and Iceland.

	Policy 1								
	non-ETS bench-mark price in €	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	91.7	65.8	-0.5	-0.4	-17.3	-0.2	0.1	-23.0	5.8
Baltic states	60.1	39.1	-0.1	-0.1	-11.4	-0.1	0.1	-12.3	6.4
Belgium	97.8	60.5	-1.2	-0.9	-23.2	-0.4	0.2	-11.8	7.9
Czech Rep.	98.3	37.3	-1.3	-1.0	-22.5	-0.5	0.3	-11.7	20.3
Denmark	111.6	75.6	-0.9	-0.7	-21.8	-0.2	0.1	-26.2	7.2
Finland	111.1	43.6	-0.7	-0.6	-32.4	-0.2	0.1	-16.3	11.6
France	64.2	55.1	-0.7	-0.5	-7.2	-0.4	0.3	-11.0	2.0
Germany	64.9	37.3	-2.7	-2.1	-14.4	-1.7	1.1	-8.4	7.3
Greece	56.4	44.5	-0.8	-0.6	-7.9	-0.6	0.4	-17.7	5.8
Hungary	47.4	37.3	0.0	0.0	-5.9	-0.1	0.0	-6.2	2.9
Ireland	53.8	46.2	-0.1	0.0	-6.0	0.0	0.0	-9.4	2.2
Italy	28.3	-	-	-	-	-	-	-	-
Netherlands	118.6	85.4	-2.0	-1.6	-19.8	-0.5	0.3	-11.7	6.9
Norway	67.3	62.3	-0.1	-0.1	-4.3	0.0	0.0	-10.3	0.9
Poland	51.9	31.1	-0.6	-0.5	-6.5	-0.6	0.4	-4.5	8.7
Portugal	62.2	42.7	-0.2	-0.1	-12.4	-0.1	0.1	-9.4	4.4
Rest of EU	103.1	43.6	-3.2	-2.6	-29.0	-1.0	0.7	-12.6	16.2
Slovakia	97.2	47.1	-0.4	-0.4	-23.8	-0.2	0.1	-14.8	16.6
Spain	73.9	46.2	-1.6	-1.3	-16.9	-0.8	0.5	-10.9	6.4
Sweden	118.1	81.0	-0.6	-0.5	-22.9	-0.1	0.1	-23.1	6.0
UK	59.0	40.9	-1.4	-1.1	-10.9	-1.0	0.7	-7.2	5.0

Table 1: Policy simulation results for minimizing abatement costs while holding abatement constant. In Benchmark: ETS price 26.7 €, Efficient price 41.9 € and Inefficiency I 1.25.

Regarding policy 2, in which the country maximizes emissions abatement while holding abatement costs constant (by shifting only part of the emissions savings in the ETS sector to the non-ETS sector), optimal carbon price floors are lower than under policy 1 and vary from 28 € in Poland to 69 € in the Netherlands. Note that this policy leaves abatement costs in the EU unchanged. However, since overall abatement increases, overall efficient costs in the EU increase which serve as reference for our inefficiency measure I (the denominator in (17)). Thus, the inefficiency of the EU carbon market decreases. Germany shows the highest potential to increase environmental effectiveness as well as cost efficiency of the EU carbon market even though the effects are rather small if not negligible: The introduction of a carbon price floor of around 33 € would lead to an EU-wide emissions reduction of 0.1% and an efficiency gain of 0.9 p.p. compared to the benchmark situation. From a national viewpoint, Germany would be able to reduce CO_2 emissions by 0.5% without any additional abatement costs.

	Policy 2								
	Carbon price floor in €	Efficient price in €	ΔI in p.p.	Δ efficient cost in EU in %	EU-wide emission change 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	54.3	41.9	-0.2	0.1	0.0	-0.1	0.1	-17.5	3.1
Baltic states	32.9	41.9	0.0	0.0	0.0	0.0	0.0	-6.6	2.9
Belgium	53.4	42.0	-0.5	0.4	0.0	-0.3	0.1	-9.7	4.3
Czech Rep.	36.5	42.1	-0.7	0.6	-0.1	-0.4	0.2	-10.8	12.0
Denmark	63.2	42.1	-0.3	0.2	0.0	-0.2	0.1	-21.3	3.7
Finland	44.5	42.0	-0.4	0.3	0.0	-0.2	0.1	-17.0	7.3
France	40.0	42.0	-0.2	0.1	0.0	-0.2	0.1	-5.8	0.9
Germany	32.9	42.1	-0.9	0.7	-0.1	-1.1	0.6	-5.1	3.6
Greece	33.8	41.9	-0.2	0.1	0.0	-0.3	0.2	-8.1	2.3
Hungary	29.3	41.9	0.0	0.0	0.0	0.0	0.0	-1.7	0.7
Ireland	33.8	41.9	0.0	0.0	0.0	0.0	0.0	-3.8	0.8
Italy	-	-	-	-	-	-	-	-	-
Netherlands	69.4	42.0	-0.6	0.5	-0.1	-0.4	0.2	-9.5	3.4
Norway	43.6	41.9	0.0	0.0	0.0	0.0	0.0	-5.7	0.4
Poland	28.4	41.9	-0.1	0.1	0.0	-0.2	0.1	-1.9	3.3
Portugal	34.7	41.9	0.0	0.0	0.0	-0.1	0.0	-5.2	2.0
Rest of EU	42.7	42.3	-1.6	1.3	-0.1	-1.0	0.4	-12.1	9.8
Slovakia	43.6	42.0	-0.2	0.2	0.0	-0.1	0.1	-12.7	9.3
Spain	39.1	42.0	-0.6	0.5	-0.1	-0.6	0.3	-7.4	3.3
Sweden	67.6	41.9	-0.2	0.2	0.0	-0.1	0.0	-19.0	3.0
UK	32.9	42.0	-0.4	0.3	0.0	-0.5	0.3	-3.4	2.0

Table 2: Policy simulation results for maximizing abatement while holding abatement costs constant. In Benchmark: ETS price 26.7 €, Efficient price 41.9 € and Inefficiency I 1.25.

Finally, we present the results for policy 3 which revisits the German climate levy proposal from 2015. In contrast to the former two policies, this policy does not allow for shifting emissions from the ETS to non-ETS sector. The abatement effort in the ETS sector is simply increased by introducing a carbon price floor which also increases abatement costs. The resulting excess emission allowances are simply retired by the government without adjusting the target in the non-ETS sector. The optimal carbon price floors for this policy option do not vary much across regions and range from 52.5 € to 55.1 €. They are optimal in the way that they minimize inefficiency measure I given by (19). The 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 55.1 € in 2020, Germany is now able to reduce overall EU ETS emissions by 4.0% and national ETS emissions by 19.2%. We also find that this policy would have little effects on the overall efficient price in which all sectors would be covered by the ETS. This price ranges from 42 €, if Ireland and Norway would introduce an additional optimal price floor, to 46 € for Germany. Yet, policy 3 which has stronger effects on EU emission levels comes at significant costs for countries introducing the price floor. In some cases (Poland and Italy), abatement costs are more than twice as high as in the bau case.

	Policy 3							
	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	52.5	42.0	-0.1	0.3	0.4	14.1	-0.1	-16.6
Baltic states	52.5	42.1	-0.2	0.4	0.6	49.4	-0.2	-22.6
Belgium	52.5	42.2	-0.4	0.8	1.1	19.8	-0.3	-9.5
Czech Rep.	53.4	42.9	-1.1	2.5	3.4	54.8	-1.0	-24.1
Denmark	52.5	42.0	-0.2	0.4	0.5	11.5	-0.1	-16.4
Finland	52.5	42.2	-0.3	0.8	1.0	44.4	-0.3	-23.3
France	52.5	42.3	-0.4	1.0	1.3	13.1	-0.4	-10.2
Germany	55.1	46.0	-4.4	10.8	14.8	72.4	-4.0	-19.2
Greece	52.5	42.7	-1.0	2.1	2.9	25.6	-0.8	-23.6
Hungary	52.5	42.0	-0.1	0.3	0.4	46.1	-0.1	-13.4
Ireland	52.5	42.0	-0.1	0.2	0.2	21.1	-0.1	-11.9
Italy	53.4	42.8	-1.0	2.3	3.2	89.6	-0.9	-8.9
Netherlands	52.5	42.2	-0.3	0.7	0.9	8.4	-0.3	-6.6
Norway	52.5	41.9	-0.0	0.1	0.1	5.9	0.0	-8.0
Poland	54.3	44.8	-3.3	7.7	10.6	99.8	-2.9	-21.8
Portugal	52.5	42.1	-0.2	0.4	0.5	39.8	-0.1	-13.9
Rest of EU	53.4	43.4	-1.7	3.9	5.4	43.7	-1.5	-18.2
Slovakia	52.5	42.1	-0.2	0.5	0.7	32.7	-0.2	-17.8
Spain	53.4	42.9	-1.2	2.7	3.7	35.7	-1.0	-13.9
Sweden	52.5	42.0	-0.1	0.2	0.3	10.4	-0.1	-13.5
UK	53.4	43.7	-2.0	4.6	6.3	44.0	-1.7	-12.1

Table 3: Policy simulation results for minimizing EU inefficiencies. In Benchmark: ETS price 26.7 €, 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 effective and efficient additional national climate policy efforts. While policy 3 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 and 2 where reduction targets are (fully or partially) shifted from the ETS to non-ETS sectors since the non-ETS targets are fixed in the EU Effort Sharing Decision (European Commission, 2009). However, our paper has shown 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 order to put our results into context, we 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 retirement of allowances and shifting of targets (policy 1 and 2) or simply retirement of allowances (policy 3). Thus, they do not imply any emission reductions and further increase inefficiencies as shown by Böhringer et al. (2008) and Heindl et al. (2014). A price floor as for instance announced in France (The Guardian, 2016) will thus further increase costs and inefficiencies in the EU because it is simply an additional amount that certain emitters have to pay on top of the ETS allowance price while their extra abatement is offset by EU ETS sectors not facing this price floor.

We find that the announced French price floor of 30 €, i.e. a tax of 25 € on top of the current ETS allowance price would increase EU ETS abatement costs by 1.1% and French abatement costs by 15.2%. It is important to note that we add a tax of 25 € on top of our ETS allowance model benchmark price of 26.7 €. However, although resulting in a higher price floor, this result may well serve as an approximation of the relative cost increase in the EU carbon market due to the introduction of a "simple" price floor. According to our policy simulations, France has generally a relatively low potential to reduce inefficiencies of the entire EU carbon market. Figure 5 shows the results of our three policy cases for selected countries, including France, depending on the national carbon price floor level. We focus on the results of the respective policy objectives which is minimizing abatement costs for policy 1, maximizing abatement for policy 2 and minimizing inefficiency measure I for policy 3.

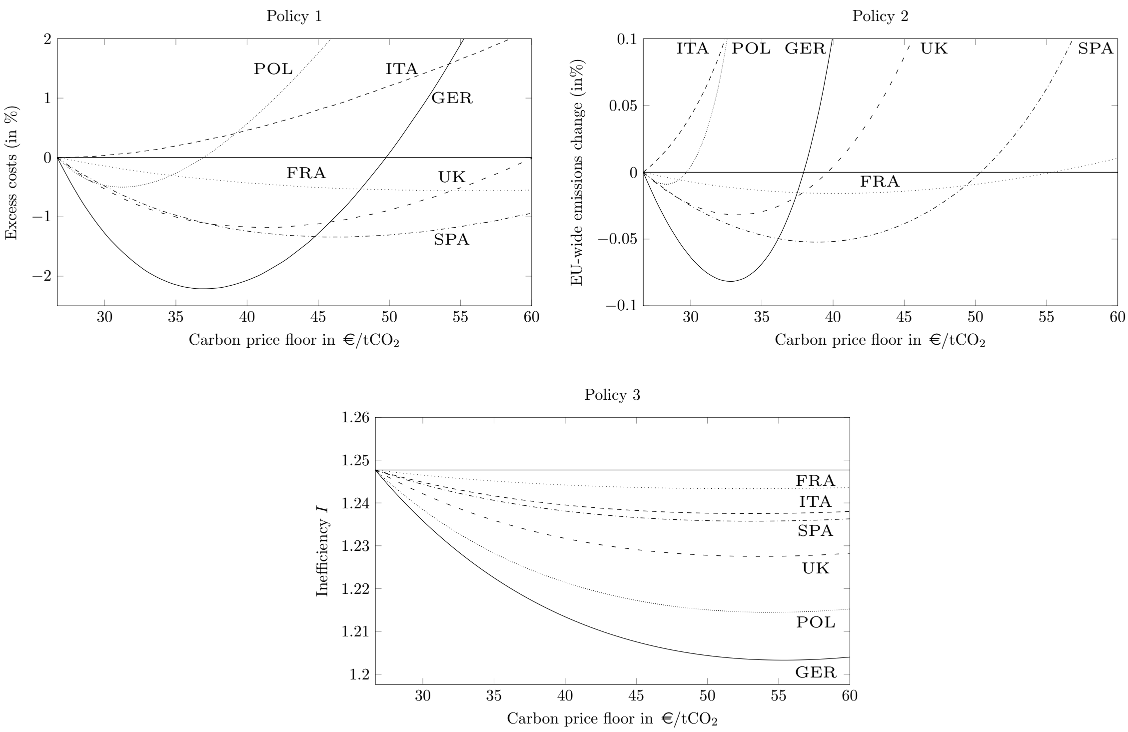


Figure 5: Policy results for selected EU countries.

The optimal carbon price floor level in France is 55 €, 40 € and 53 € for policy 1, 2 and 3, respectively. These price floors would lead to a national respective EU-wide cost reduction of 7.2%and 0.5% if introducing policy 1, an emissions reduction of only 0.02 % if introducing policy 2 and a decrease of cost inefficiency I by 0.4 p.p. if introducing policy 3. Hence, apart from its low 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. The actually planned price floor would at least not increase inefficiencies if one of our three policy options is introduced. 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 9.3% and German abatement costs by 51.0%. 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 the policy measure. The first two policy options should aim for price floor level of 37 € and 33 € while the latter for 55 €. Finally, we may compare 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 3.5% and UK costs by 31.3%. Allowing for our alternative policy designs, we estimate an optimal price floor level of 41 €, 33 € and 53 € for policy 1, 2 and 3, respectively. These would lead to an EU-wide cost reduction of 1.1% if introducing policy 1, an emissions reduction of 0.03% if introducing policy 2 and a decrease of cost inefficiency I by 2 p.p. if introducing policy 3. 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 three policy cases.

All in all, we find that a national tax policy (or price floor) design in which emissions are shifted to the non-ETS sector has the most potential to reconcile with the EU climate policy framework. Especially, policy 2 is very promising since national policymakers are able to increase abatement efforts while at the same time reduce cost inefficiencies in the EU carbon market. According to our stylized analysis, the German climate levy proposal would have been a highly costly policy option while its cost efficiency results can hardly be determined since both, costs and revenues, change. Its efficiency may however be approximated by a cost-markup factor of the separated carbon market that we introduced in this paper.

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 non-ETS sector or retired due to the price floor. Policymakers would need to have reliable estimates of abatement costs for specific sectors or firms. Moreover, there exist huge sectoral differences in abatement costs within the ETS and non-ETS sectors (recall Figure 7, 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 3, it also depends on which sectors are taxed and thus, how many emission allowances will be retired. Yet, a pragmatic approach may be to implement a price floor in the order of 30 € (which is a lower bound in our estimations), to use the revenue to buy EU ETS allowances and retire them and then reduce abatement efforts in the non-ETS sectors by the same amount (policy 1) or a smaller amount (policy 2). In most countries where there is strong evidence that more abatement should take place within the ETS and less outside, these policies are likely to decrease overall costs (shift all emissions) or to achieve additional emission reductions at basically no extra costs.

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 reduce overall emissions (and thus be effective) and reduce overall abatement costs (and thus be efficient). 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 no to be the case if national policies are designed in a way that allows for shifting emissions from the ETS to non-ETS sectors as well as retiring emission allowances. Therefore, we introduce three carbon pricing policy options that i) minimize national abatement costs while keeping abatement constant, ii) maximize national abatement while keeping abatement costs constant and iii) minimize EU inefficiencies by simply retiring emission allowances as stipulated by the Germany climate levy proposal. In a simple theoretical framework with two countries and two sectors, we derive the optimality conditions for the carbon price floor level of each policy. Moreover, we are able to derive a closed form solution for the optimal price floor level. According to that, efficiency is the highest at a price level equaling a weighted sum of the price differentials between ETS and non-ETS sectors.

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 minimizing national abatement costs by shifting emissions from the ETS to non-ETS sector, Germany is able to reduce EU-wide costs by 2.1% when introducing a price floor of 37 € in their EU ETS sector in 2020. At the same time German abatement costs are reduced by 14.4%. If Germany maximizes its national abatement while holding abatement costs constant, it is able to reduce EU-wide emissions by 0.1% when introducing a price floor of 33 € in 2020. Finally, if Germany simply increases abatement efforts in the ETS sector while retiring allowances, it is able to reduce the cost-markup factor of the separated carbon market by 4.4 p.p. Yet, this increases national abatement costs by 72.4%.

Despite the stylized nature of our three policies, we conclude that national climate policy efforts can indeed be efficient in the current EU policy setting. Our first two policy options, shifting abatement 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 and very promising. Another possibility within the current EU policy framework is to simply combine carbon price floors in national EU ETS sectors with the retirement of EU ETS allowances. This third policy option is effective but its efficiency cannot be easily determined. Naturally, this policy also comes at potentially very high additional costs for the country undertaking this policy.

A. Derivations

1. Assuming linear MAC curves of the form $c_i'(x_i) = a_i x_i$ and $c_i'(y_i) = b_i y_i$ for the ETS and non-ETS sector, respectively, and solving the first order condition (12) for the additional abatement quantity δ_1 leads to

$$\frac{\partial C_1(\tilde{x}_1, \tilde{y}_1, \delta_1, z)}{\partial \delta_1} = a_1(\tilde{x}_1 + \delta_1) - b_1(\tilde{y}_1 - \delta_1) \stackrel{!}{=} 0$$
$$\Leftrightarrow a_1\delta_1 + b_1\delta_1 = b_1\tilde{y}_1 - a_1\tilde{x}_1$$
$$\Leftrightarrow \delta_1^* = \frac{(\pi_1 - \rho)}{a_1 + b_1}.$$

Since

$$\delta_1 = \hat{x}_1 - \tilde{x}_1 = \frac{\rho + \tau_1}{a_1} - \frac{\rho}{a_1} = \frac{\tau_1}{a_1},$$

the optimal tax level is

$$\tau_{1,pol1}^* = \frac{a_1(\pi_1 - \rho)}{a_1 + b_1}.$$

2. Solving the system of equations (14)-(16) for the unknown δ_1 leads to the optimal tax level

$$\tau_{1,pol2}^* = \frac{\sqrt{a_1 b_1}\sqrt{\pi_1 z_{y_1} + \rho\tilde{x}_1}}{\sqrt{a_1 + b_1}} - \rho.$$

3. Assuming linear MAC curves as in A.1 and inserting them into (18) leads to the objective function

$$I_{pol3} = \frac{C(\tilde{x}_i, \tilde{y}_i, \delta_1, \bar{z})}{C(x_i^*, y_i^*, \bar{z})} = \frac{a_1(\tilde{x}_1 + \delta_1)^2 + b_1\tilde{y}_1^2 + a_2\tilde{x}_2^2 + b_2\tilde{y}_2^2}{(z + \delta_1)^2\Omega}$$

with

$$\Omega = \Big(a_1\big(\frac{a_2 b_1 b_2}{\gamma}\big)^2 + b_1\big(\frac{a_1 a_2 b_2}{\gamma}\big)^2 + a_2\big(\frac{a_1 b_1 b_2}{\gamma}\big)^2 + b_2\big(\frac{a_1 a_2 b_1}{\gamma}\big)^2\Big)$$

where

$$\gamma = a_1 a_2 b_1 + a_1 a_2 b_2 + a_1 b_1 b_2 + a_2 b_1 b_2.$$

Then, by applying the quotient rule, the first order condition is given by

$$\frac{\partial I_{pol3}}{\partial \delta_1} = \frac{\frac{\partial C(\tilde{x}_i, \tilde{y}_i, \delta_1, \bar{z})}{\partial \delta_1}}{\frac{\partial C(x_i^*, y_i^*, \bar{z})}{\partial \delta_1}}$$
$$= \frac{2a_1(\tilde{x}_1 + \delta_1)(z + \delta_1)^2\Omega - 2(z + \delta_1)\Omega\big(a_1(\tilde{x}_1 + \delta_1)^2 + b_1\tilde{y}_1^2 + a_2\tilde{x}_2^2 + b_2\tilde{y}_2^2\big)}{(z + \delta_1)^4\Omega^2} \stackrel{!}{=} 0. \quad (25)$$

Solving (25) for unknown δ_1 leads to

$$
\begin{aligned}
& a_1(\tilde{x}_1 + \delta_1)(z + \delta_1) - a_1(\tilde{x}_1 + \delta_1)^2 - b_1\tilde{y}_1^2 - a_2\tilde{x}_2^2 - b_2\tilde{y}_2^2 = 0 && (26)\\
\Leftrightarrow\ & a_1(\tilde{x}_1 + \delta_1)(z + \delta_1) - a_1(\tilde{x}_1 + \delta_1)^2 - \pi_1\tilde{y}_1 - \pi_2\tilde{y}_2 - \rho\tilde{x}_2 = 0 && (27)\\
\Leftrightarrow\ & a_1(\tilde{x}_1 z + \tilde{x}_1\delta_1 + \delta_1 z + \delta_1^2 - \tilde{x}_1^2 - 2\tilde{x}_1\delta_1 - \delta_1^2) - \pi_1\tilde{y}_1 - \pi_2\tilde{y}_2 - \rho\tilde{x}_2 = 0 && (28)\\
\Leftrightarrow\ & a_1(\tilde{x}_1 z - \tilde{x}_1\delta_1 + \delta_1 z - \tilde{x}_1^2) - \pi_1\tilde{y}_1 - \pi_2\tilde{y}_2 - \rho\tilde{x}_2 = 0 && (29)\\
\Leftrightarrow\ & \delta_1(a_1 z - a_1\tilde{x}_1) = \pi_1\tilde{y}_1 + \pi_2\tilde{y}_2 + \rho\tilde{x}_2 - a_1\tilde{x}_1 z + a_1\tilde{x}_1^2 && (30)\\
\Leftrightarrow\ & \delta_1 = \frac{\pi_1 z_{y_1} + \pi_2 z_{y_2} + \rho z_x - \rho z}{a_1 z - \rho} && (31)\\
\Leftrightarrow\ & \delta_1 = \frac{Q - \rho z}{a_1 z - \rho}, && (32)
\end{aligned}
$$

with target weighted price index

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

Finally, since $\delta_1 = \frac{\tau_1}{a_1}$, the optimal tax level of policy 3 is given by

$$\tau^*_{1,pol3} = \frac{a_1(\frac{Q}{z} - \rho)}{a_1 - \frac{\rho}{z}}. \tag{33}$$

B. Tables

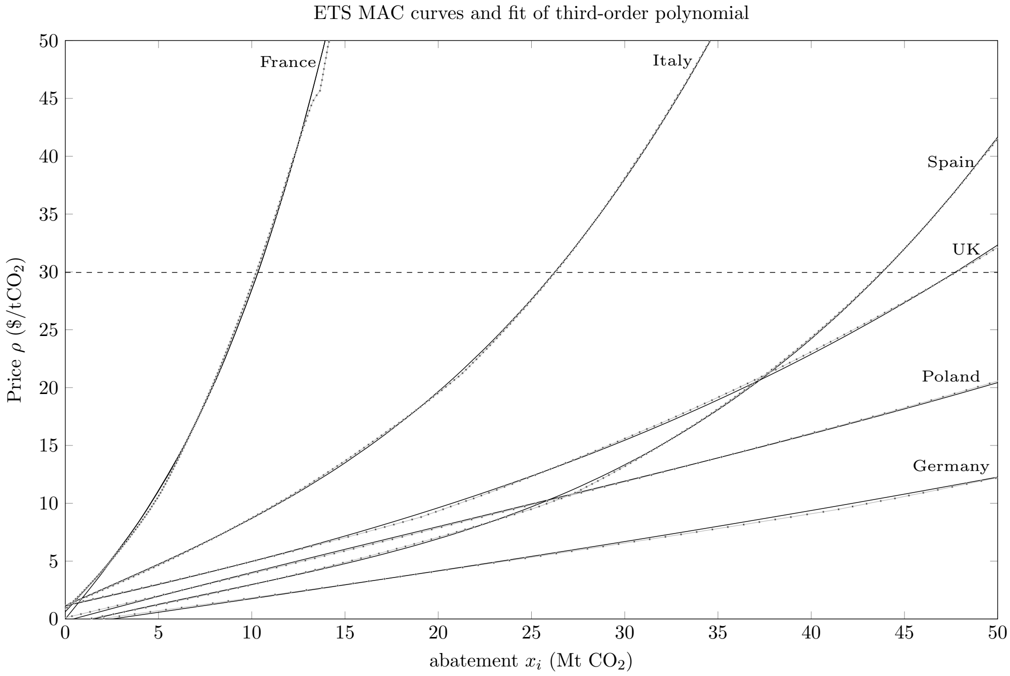
Data: Regarding the ETS sectors, we use historic emissions from 2008 to 2012 of the European Environment Agency (2016) while from 2013 to 2020 applying a reduction of 1.74% p.a. for each EU region as envisaged by phase 3 of the EU ETS.[10] The resulting reduction factors for the ETS sectors in 2020 compared 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 4: EU emission targets and resulting reduction factors for 21 regions in the year 2020.

[10] See 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.

C. Figures



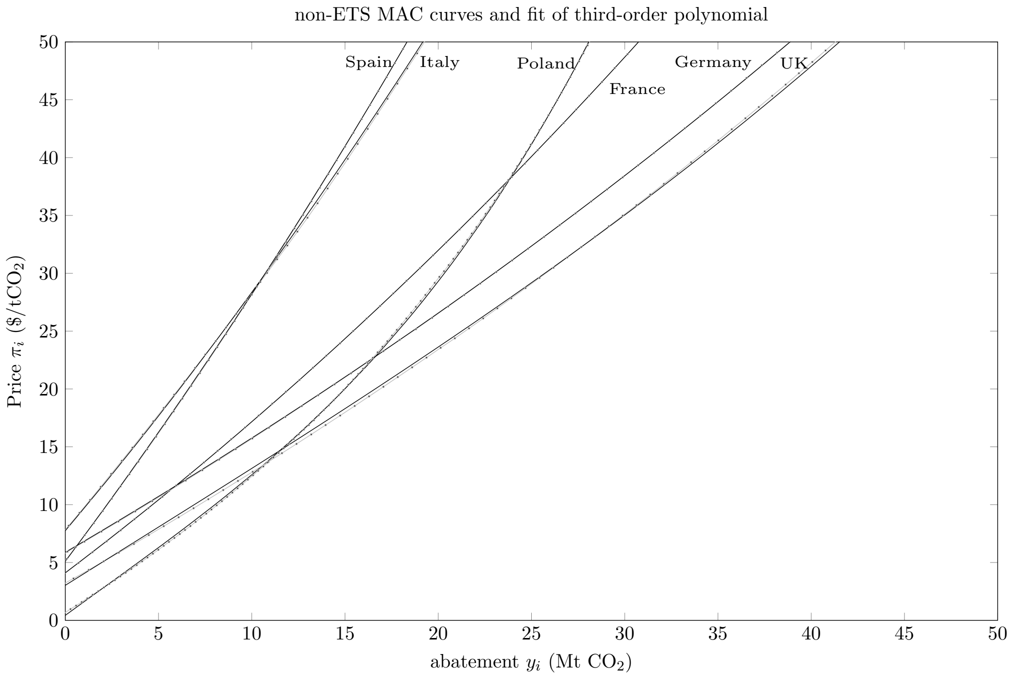
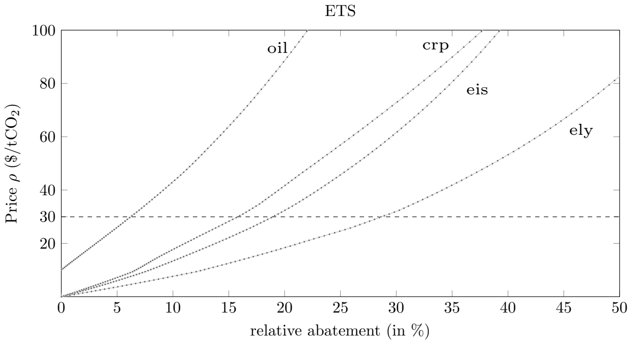
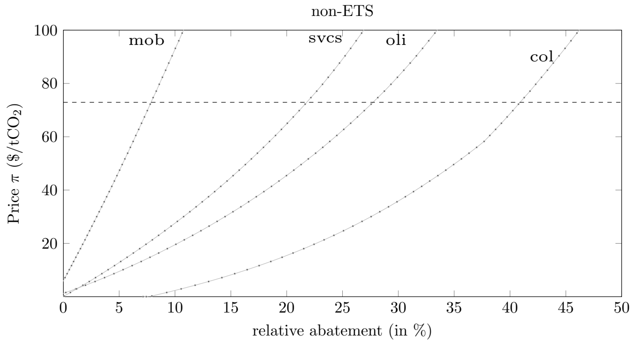


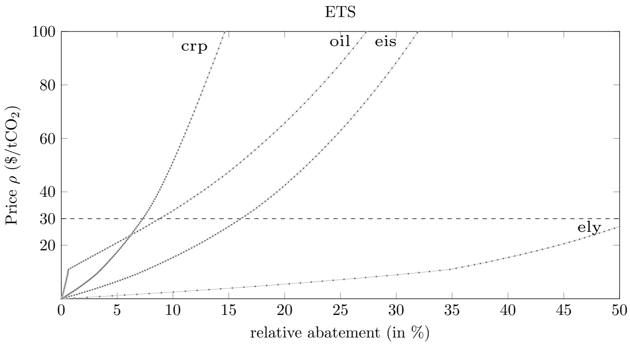
Figure 6: OLS fits of non-linear MAC curves for selected EU countries and both sectors.



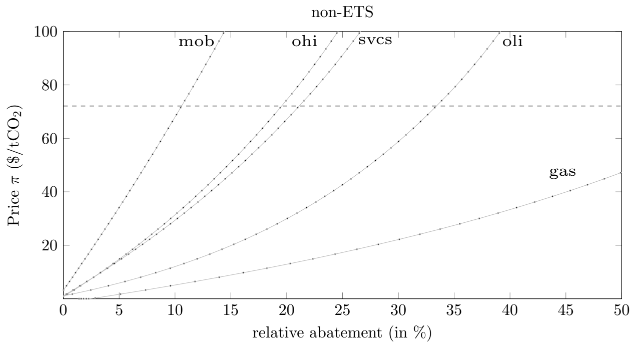
(a) Germany's sectoral MAC curves in ETS



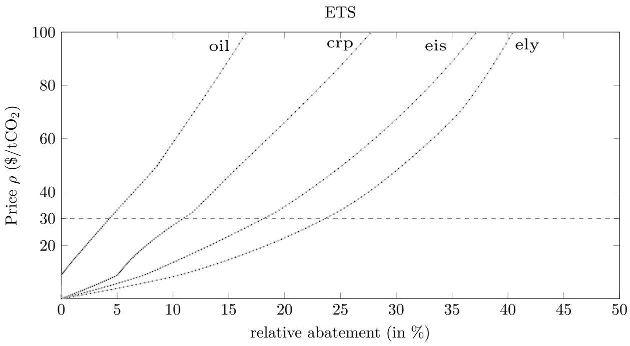
(b) Germany's sectoral MAC curves in non-ETS



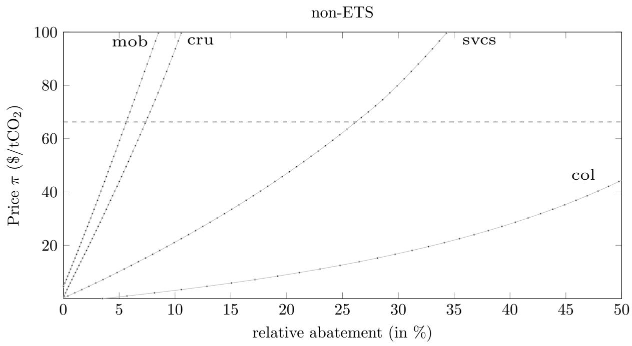
(c) France's sectoral MAC curves in ETS



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

ETS sectors: oil=refined oil products, crp=chemical and rubber products, eis=energy intensive sectors, ely=electricity.
non-ETS sectors: mob=mobility, svcs=services, ohi=other heavy industries, oli=other light industries, col=coal, cru=crude oil production.

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