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Higher Price, Lower Costs? Minimum Prices in the EU Emissions Trading Scheme

By JAN ABRELL, SEBASTIAN RAUSCH, AND HIDEMICHI YONEZAWA *

This paper examines the efficiency and distributional impacts of introducing a price floor in an emissions trading system (ETS) when environmental regulation is partitioned. We theoretically characterize the conditions under which a price floor enhances welfare. Using a multi-country multi-sector numerical general equilibrium model of the European carbon market, we find that moderate minimum price levels in the EU ETS can reduce the costs of EU climate policy by up to thirty percent and yield outcomes close to uniform carbon pricing. Moreover, most of the EU Member States would gain. Our results are robust with respect to parametric uncertainty in production and consumption technologies. (JEL H23, Q52, Q58, C68).

While emissions trading systems (ETS) have become centerpieces of market-based environmental regulation in many countries, they have been shown to suffer from two major issues. First, they typically cover only a subset of emissions thereby undermining static cost-effectiveness of pollution control as marginal abatement costs (MAC) are not equalized across all sources (Böhringer, Hoffmann and Manrique-de Lara-Penate, 2006; Böhringer, Dijkstra and Rosendahl, 2014). Second, exogenous shocks (economic recessions, fuel prices, technology shocks) and overlapping environmental policies (Fischer and Preonas, 2010; Böhringer and Rosendahl, 2010) can lead to unforeseen impacts on the ETS permit price. Importantly, this may reduce the investment incentives for low-cost pollution-extensive “clean” future technologies with negative effects for dynamic cost-effectiveness. The first—and still by far the biggest—international system for trading greenhouse gas emission (GHG) allowances, the EU ETS also faces these issues, namely that a) the European Union (EU)’s climate policy is highly partitioned with only about one half of EU’s emissions covered by the EU ETS¹ and b) the price for

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¹The EU ETS covers about 45% of total EU-wide emissions, mainly from electricity and energy-intensive installations. By 2020 and compared to 2005 levels, a 21% reduction in emissions has to come from sectors covered by the EU ETS and an additional 10% reduction from non-trading sectors covered by

EU emissions allowances is conceived to be too low (Nordhaus, 2011; EU, 2014).²

This paper examines whether and by how much the abatement costs of achieving a given environmental target under partitioned climate regulation that is majorly based on an international ETS can be reduced by introducing a minimum price for ETS permits. We theoretically characterize the conditions under which a price floor for ETS permits enhances static cost-effectiveness by reducing the differences in marginal abatement costs (MAC) across the partitions of environmental regulation. Assuming that the environmental target always has to be fulfilled, we show that a higher ETS permit price—induced by a binding minimum price policy—reduces total abatement costs if MAC across countries and sectors in the non-ETS partition are on average higher than the minimum ETS price.

Our theoretical analysis is complemented by an empirical, quantitative assessment of the efficiency and distributional impacts of introducing a minimum price in the EU ETS to achieve the emissions reductions goals of EU Climate Policy (EU, 2008). Employing a numerical multi-country multi-sector general equilibrium model of the European carbon market, we find that ETS price floors on the order of \$50-70 per ton of CO₂ can reduce the welfare costs of achieving EU climate policy targets by 20-30 percent relative to current policy. The efficiency gains are mainly driven by two effects: (1) a decrease in the difference of MAC between firms in the ETS and non-ETS partition and (2) the reduction in adverse tax interaction effects arising from shifting abatement away from sectors that are subject to high pre-existing fuel taxes and are not covered by the EU ETS (such as, for example, transportation). Importantly, we find that an effective minimum price policy can achieve outcomes close to that would be obtained with uniform carbon pricing if environmental regulation was not partitioned.

The efficiency argument for a minimum price in the EU ETS is strengthened by our finding that the likely distributional impacts among the EU Member States do not adversely affect regional equity. Introducing a minimum ETS permit price entails welfare gains for the large majority of countries, with the gains of winning countries vastly exceeding the losses of losing countries. We thus argue that—given the feasibility of inter-country transfers within the EU—the efficiency gains from introducing a minimum EU ETS price can be shared among all countries in a way that makes each country better off.

Our main result that a minimum ETS permit price would bring about sizeable welfare gains relative to current EU climate policy is robust with respect to uncertainty in parameterizing production and consumption technologies. Using systematic (Monte Carlo-type) sensitivity analysis, we find that optimal minimum

the “Effort Sharing Decision” under the EU’s “2020 Climate and Energy Package”—including transport, buildings, services, small industrial installations, and agriculture and waste. Sources not covered under the EU ETS are regulated directly by member states, often relying on renewable support schemes and technology policies.

²This normative judgement is mainly based on the observations that the estimates of the social cost of carbon tend to be substantially higher (Tol, 2009; Knopf et al., 2014; US EPA, 2015) and that a too low price signal is detrimental for low-carbon investments.

price policies guarantee welfare gains between 15-40 percent.

The present paper contributes to the existing literature in several ways. First, the paper is closely related to the “safety valve” literature that has scrutinized the idea of introducing price collars into a cap-and-trade system of emissions regulation to limit the costs of meeting the cap (Jacoby and Ellerman, 2004; Pizer, 2002). Hourcade and Gershi (2002) carried this idea over into the international discussion by proposing that compliance with the Kyoto Protocol might be met by paying a “compliance penalty”. Philibert (2009) shows in a quantitative analysis that price caps could significantly reduce economic uncertainty stemming primarily from unpredictable economic growth and energy prices thus lowering the costs for global climate change mitigation policy. Both price ceilings and price floors can reduce risk and price volatility in carbon markets (Grubb and Neuhoff, 2006), and can thus make the introduction of ETS more acceptable. The “safety valve” literature—building closely on the seminal contribution made by Roberts and Spence (1976)—does, however, not consider the issue of hybrid approaches to controlling pollution under an ETS in the context of partitioned environmental regulation. Moreover, this strand of the literature is predominantly concerned with analyzing price ceilings to limit the costs of climate mitigation policy; instead, we focus on price floors as a way to limit costs. Related work that has examined introducing price floors in an ETS (Wood and Jotzo, 2011; Fell and Morgenstern, 2010) have abstracted from partitioned environmental regulation which is a distinct feature of real-world climate policies in many countries.

Second, a number of studies has quantified the efficiency costs of partitioned regulation caused by limited sectoral coverage of the EU ETS (Böhringer, Hoffmann and Manrique-de Lara-Penate, 2006; Böhringer, Dijkstra and Rosendahl, 2014) or due to strategic partitioning (Böhringer and Rosendahl, 2009; Dijkstra, Manderson and Lee, 2011). While this literature has importantly contributed to informing the climate policy debate about cost-effective regulatory designs, it has not investigated the issue of price floors for emissions trading.

Third, a small number of recent papers examines the idea of introducing a quantity-based adjustment mechanism to the EU ETS (Fell, 2015; Schopp, Acworth and Neuhoff, 2015; Kollenberg and Taschini, 2015; Ellerman, Valero and Zaklan, 2015; Perino and Willner, 2015). The so-called “Market Stability Reserve (MSR)” —to be introduced in Phase 4 of the EU ETS—aims at rectifying the structural problem of allowances surplus by creating a mechanism according to which annual auction volumes are adjusted in situations where the total number of allowances in circulation is outside a certain predefined range (EU, 2014).³ While we do not attempt to provide an explicit analysis of the MSR, the MSR can be viewed as effectively introducing a lower bound on the permit price.⁴ We

³Perino and Willner (2015), for example, focuses on the impact of the MSR on price and emission paths, and Kollenberg and Taschini (2015) on characterizing the dependencies between the allowance allocation adjustment rate and the market equilibrium dynamics.

⁴Abrell and Rausch (2016) analyze adding a price collar or lower and upper bounds on abatement in an ETS under partitioned environmental regulation when the regulator faces uncertainty about future

thus contribute to the ongoing discussion about the MSR by providing the first analysis of the efficiency and distributional impacts of a ETS price floor in the context of partitioned EU climate policy.

The remainder of the paper is organized as follows. Section I presents our theoretical analysis of permit price floors under partitioned environmental regulation. Section II describes our quantitative, empirical framework that we use to analyze the effects of a price floor in the context of the EU ETS and EU Climate Policy. Section III describes our computational thought experiments, and Section IV presents and discusses the findings from our empirical quantitative analysis. Section V concludes.

I. The Theoretical Argument

In this section, we sketch our theoretical argument for why introducing a minimum price in an ETS in the context of partitioned environmental regulation can potentially decrease abatement costs. Although the reasoning below fits alternative applications, we let climate change and CO₂ abatement policies guide the modeling.

A. Basic setup

FIRMS' ABATEMENT COSTS.—We consider an economy which is composed of multiple countries, indexed by $r = 1, \dots, R$. There exist polluting firms mapped to countries, indexed by $i, j = 1, \dots, I$, that produce CO₂ emissions (for example, as a result of producing output). a_{ir} denotes the amount of emissions abatement by firm i in country r . Abatement cost functions $C_{ir}(a_{ir})$ are assumed to be continuous and twice differentiable, strictly convex ($C'_{ir} := \partial C_{ir} / \partial a_{ir} > 0$ and $C''_{ir} := \partial^2 C_{ir} / \partial a_{ir}^2 > 0$), and independent from one another ($\partial C'_{ir} / \partial a_{jr} = \partial^2 C_{ir} / \partial a_{ir} \partial a_{jr} = 0, \forall i \neq j$).

POLICY DESIGN PROBLEM.—The regulator is faced with the problem of achieving an exogenously given and fixed abatement requirement of A at the lowest possible abatement costs:⁵

$$\Psi \equiv \sum_{i,r} C_{ir}(a_{ir}).$$

The major premise underlying our analysis is that the regulation of CO₂ emissions is partitioned: firms uniquely belong to either of two partitions where one partition, denoted by T , is regulated by an ETS that encompasses multiple countries and where the second partition, denoted by N , is composed of strictly national regulatory measures. We assume that emissions control in the partition N is achieved in a cost-effective way, i.e. through a carbon tax or a national cap-and-trade system.

baseline emissions and firms' abatement technologies.

⁵As we are interested in examining the effects of introducing an ETS price floor for an exogenously set emissions target, we abstract here from explicitly including the benefits from averted pollution.

Given the abatement target, the choice of instruments, and the assignment of firms to the partitions, the policy design problem involves allocating total abatement Λ across firms in order to minimize Ψ . $A_T \geq 0$ and $A_N \geq 0$ denote the abatement budget for the ETS partition and the *joint* budget for the N partition, respectively. The overall abatement target is achieved through abatements in either partition: $A_T + A_N = \Lambda$. As non-trading firms are regulated by strictly national policies, A_N has to be further divided among countries. Let $A_{Nr} \geq 0$ denote the abatement requirement of the non-trading sector in region r with $\sum_r A_{Nr} = A_N$. The share for each country's non-trading sector in the overall non-trading abatement budget is then given by $\lambda_r^N := A_{Nr}/A_N$ where $\lambda_r^N \in [0, 1]$.

B. Cost-effective abatement

The cost-effective solution to the problem of allocating Λ across *all* firms serves as a useful benchmark; it would also reflect a situation in which partitioned environmental regulation is absent. In such a case, the regulator can determine both the split between the ETS and non-ETS partitions and how the non-ETS abatement budget is divided among firms, thus effectively choosing A_T and A_{Nr} $\forall r$.

The policy design problem is then given by:

$$\begin{aligned}
 (1) \quad & \min \sum_{i,r} C_{ir}(a_{ir}) \\
 & \text{s.t. } A_T + \sum_r A_{Nr} = \Lambda \quad (P) \\
 & \sum_r a_{Tr} \geq A_T \quad (P_T) \\
 & a_{Nr} \geq A_{Nr} \quad (P_{Nr}) \\
 & A_T, A_{Nr} \geq 0,
 \end{aligned}$$

where the respective dual variable (or shadow price) is shown in parentheses for each constraint. P is the dual variable on the market clearing condition for overall abatement (first constraint) and reflects the theoretically optimal overall permit price in a fully integrated carbon market absent partitioned environmental regulation. P_T and P_{Nr} are the permit or carbon price which is complementary to the market clearing condition in the ETS and national non-ETS partitions (second and third constraints), respectively.

Deriving the Karush-Kuhn-Tucker (KKT) conditions for the problem in (1)

yields:⁶

$$\begin{aligned} C'_{Tr} &\geq P_T && \perp a_{Tr} \geq 0 \quad \forall r \\ C'_{Nr} &\geq P_{Nr} && \perp a_{Nr} \geq 0 \quad \forall r \end{aligned}$$

$$\begin{aligned} P_T &\geq P && \perp A_T \geq 0 \\ P_{Nr} &\geq P && \perp A_{Nr} \geq 0 \quad \forall r. \end{aligned}$$

Together, these conditions together imply the standard “equimarginal” principle according to which total abatement costs are minimized if (1) all carbon prices are equalized and (2) all firms should choose a level of abatement that equalizes their marginal abatement costs with the uniform carbon price level. In particular, note that under such an idealized “first-best” policy setting, there does not exist any role for introducing minimum carbon prices.

C. Permit price floors when regulation is partitioned

With partitioned environmental regulation, it seems most plausible to view the partition of the emissions budget between partitions and across countries as being determined exogenously. In all likelihood, the partitioning of emissions budgets will be sub-optimal, thus deviating from the cost-effective solution characterized in Section I.B.

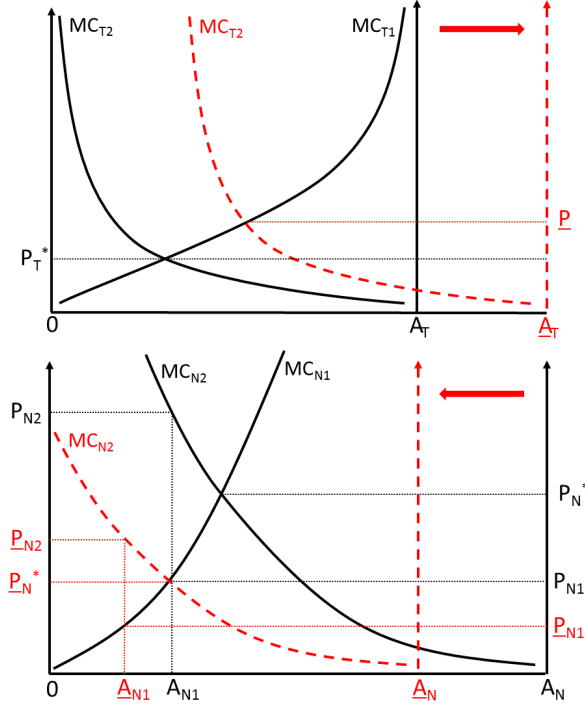
For the case with two countries, such a situation is portrayed by the black (solid) curves in Figure 1. Two types of inefficiencies become visible. First, given a pre-determined allocation of the emissions budget among non-ETS firms (across regions), indicated here by A_{N1} , the MACs are not equalized within the non-ETS partition. This would only be achieved at P_N^* which is, however, not attainable given A_{N1} . Second, the carbon price in the ETS partition achieved through emissions trading, P_T^* , deviates from the realized MAC in the non-ETS partition (P_{N1} and P_{N2}) thus leading to excess costs from falsely allocating emissions budgets between the ETS and non-ETS partitions.

How does the introduction of a minimum price on ETS permits affect the outcome? The red (dashed) curves portray a case (out of many possible cases) where we assume that there is a binding price floor, i.e. $\underline{P} > P_T^*$. The binding minimum price leads to an increase in abatement in the ETS sector which is reflected by extending the horizontal axis in the upper panel from A_T to \underline{A}_T . As the overall emissions reduction target always has to hold, the increased abatement in the ETS partition is counterbalanced by a reduction in abatement in the non-ETS partition, reflected by shrinking the horizontal axis in the lower panel from A_N to \underline{A}_N .

If one assumes that MACs in the non-ETS partition are equalized, introducing

⁶We use the perpendicular sign “ \perp ” as short hand notation for the KKT complementary slackness conditions, i.e., $f(x) \geq 0, x \geq 0$ reads as three conditions: $f(x) \geq 0, x \geq 0, f(x) * x = 0$.

Figure 1. Non-optimal partitioned environmental regulation without and with a minimum price on ETS permits (for the case with two countries)



Notes: The upper and lower panel shows abatement and MAC functions for two countries for the T and N partition, respectively. The horizontal axis shows the sectoral abatement target without (A_i) and with (\underline{A}_i) a minimum price on ETS permits, respectively. Vertical axes show the MAC or the carbon price measured in €/ton CO₂. MC_{ir} denotes the MAC function for firm i in country r . MC_1 (MC_2) is shown from left to right (right to left) on the horizontal axis. MAC functions are unaltered; the MAC functions for country 2 are shifted from the black solid curves (representing the case without a minimum price) to the red dashed curves (representing the case with a minimum price).

a minimum price on ETS permits would reduce the uniform, non-ETS carbon price from P_N^* to \underline{P}_N^* . The carbon prices in the two partitions thus move closer together, in turn increasing the cost-efficiency (assuming that initially, i.e. before the introduction of the minimum price, $P_T^* < P_N^*$ as shown in Figure 1). If one assumes that relative abatement across firms within the non-ETS partition, λ_r^N , stays the same. With the new, lower abatement target for the non-ETS partition, \underline{A}_N , the *absolute* regional abatement targets are altered, indicated by \underline{A}_{N1} . Given MAC functions as assumed in Figure 1, this diminishes the difference of MACs across regions as compared to the initial situation without minimum ETS price.

While this enhances the cost-effectiveness for the non-ETS partition, the effect on *total* abatement costs is, however, ambiguous as the cost reduction in the non-ETS partition has to be weighed against the increase in abatement costs in the

ETS partition. Intuitively, if the non-ETS carbon price of a country is above the ETS price, overall abatement costs decrease because abatement is shifted from the partition with higher to the one with lower MACs. In contrast, if MACs of a country are below the established minimum ETS price, overall costs rise. In Figure 1, it is therefore unclear whether the introduction of a minimum price on ETS permits increases or decreases total abatement costs.

We can, however, characterize the conditions under which the introduction of a binding minimum ETS price decreases or increases total abatement cost. Consider marginally increasing the ETS price which increases the abatement in the ETS partition (given a monotonously increasing MAC curve). As total abatement is constant, overall abatement in the non-ETS partition decreases. Thus,

$$(2) \quad dA_{Nr} = -\phi_r dA_T,$$

where $\phi_r \geq 0$ denotes how the decrease in the abatement of the non-ETS partition, dA_T , is distributed across regions, and where $\sum_r \phi_r = 1$.

Using equation (2), the change in total abatement cost in response to a *marginal* change in the ETS price is given by:

$$\begin{aligned} \frac{\partial \Psi}{\partial P_T} &= \sum_r \left[\frac{\partial C_{Tr}}{\partial P_T} + \frac{\partial C_{Nr}}{\partial P_T} \right] \\ &= \sum_r \left[C'_{Tr} \frac{\partial a_{Tr}}{\partial P_T} + C'_{Nr} \frac{\partial A_{Nr}}{\partial P_T} \right] \\ &= \sum_r \left[C'_{Tr} \frac{\partial a_{Tr}}{\partial P_T} - \phi_r C'_{Nr} \frac{\partial A_T}{\partial P_T} \right]. \end{aligned}$$

Assuming cost-minimizing firm behavior for the ETS and non-ETS partitions, MACs are equal to the respective carbon price, i.e. $C'_{Tr} = P_T$ and $C'_{Nr} = P_{Nr}$, $\forall r$. The change in total abatement cost can hence be written as:

$$(3) \quad \frac{\partial \Psi}{\partial P_T} = \sum_r \left[\frac{\partial a_{Tr}}{\partial P_T} P_T - \phi_r \frac{\partial A_T}{\partial P_T} P_{Nr} \right].$$

Exploiting the fact that $\sum_r \frac{\partial a_{Tr}}{\partial P_T} = \frac{\partial A_T}{\partial P_T}$, we can further simplify to obtain:

$$(4) \quad \frac{\partial \Psi}{\partial P_T} = \frac{\partial A_T}{\partial P_T} \left[P_T - \sum_r \phi_r P_{Nr} \right],$$

which leads to the following proposition:

PROPOSITION 1: *Given strictly convex abatement cost functions in the ETS and non-ETS partitions, a marginal change in the emissions permit price in the ETS partition decreases (increases) total costs of reducing a given abatement tar-*

get if the ETS permit price is below (above) the weighted average of regional non-ETS carbon prices with weights equal to the shares that determine the cross-country distribution of the total abatement decrease in the non-ETS partition.

PROOF: Equation (4) and noting that $\partial A_T / \partial P_T > 0$. \square

Proposition 1 bears out a simple intuition. A marginal increase in the ETS price shifting abatement from the non-ETS to the ETS partition decreases total abatement costs if abatement is shifted from high-cost to low-cost abatement opportunities. If the non-ETS marginal abatement costs (i.e., the non-ETS carbon prices) for all countries are above (below) the permit price, then the ETS price increase leads to a decrease (increase) in total abatement cost independent from the cross-country distribution of the abatement reduction in the non-ETS partition (i.e., independent from ϕ_r). If, however, some regional prices are below and others are above the minimum ETS price, whether or not total abatement costs decrease depends on how the abatement reduction is distributed across countries in the ETS partition.

Importantly, Proposition 1 is only valid for a marginal change in the ETS permit price. If, however, the introduction of a minimum ETS permit price is non-marginal, the implied abatement decrease in the non-ETS partition affects the MAC in the non-ETS partition. Given the assumption of monotonically increasing MAC curves in both partitions, a binding minimum price that raises P_T decreases the abatement target in the non-ETS partition, hence $\partial C'_{Nr} / \partial P_T = \partial P_{Nr} / \partial P_T < 0$. It is thus straightforward to see that for sufficiently large increases in P_T , the term in squared brackets in equation (4) will become positive.

The introduction of a minimum ETS permit price that non-incrementally raises the permit price level from P_T^0 to \underline{P} decreases total abatement costs if:

$$(5) \quad \int_{P_T^0}^{\underline{P}} \frac{\partial A_T}{\partial P_T} \left[P_T - \sum_r \phi_r P_{Nr} \right] dP_T < 0.$$

PROPOSITION 2: *Given continuous and strictly convex abatement cost functions in the ETS and non-ETS partitions, the introduction of a minimum ETS permit price that increases the ETS price from P_T^0 to \underline{P} and decreases the non-ETS prices from P_{Nr}^0 to P_{Nr}^1 reduces total abatement costs*

(i) if $[P_T^0 - \sum_r \phi_r P_{Nr}^0] < 0$ (necessary condition)

(ii) and if $[\underline{P} - \sum_r \phi_r P_{Nr}^1] \geq 0$ (sufficient condition).

PROOF: From condition (5) and as $\partial A_T / \partial P_T > 0$, abatement costs are reduced at a given point if difference between the minimum ETS price and the weighted average of regional non-ETS prices is negative. This difference is increasing in the

minimum price, i.e. $\partial(P_T - \sum_r \phi_r P_{Nr}) / \partial \underline{P} > 0$ as $1 - \sum_r \phi_r \underbrace{\frac{\partial^2 C_{Nr}}{\partial A_{Nr}^2}}_{>0} \underbrace{\frac{\partial A_{Nr}}{\partial A_T}}_{<0} \underbrace{\frac{\partial A_T}{\partial \underline{P}}}_{>0} >$

0 which follows from the assumption of convex MAC functions and equation (2). If the necessary condition does not hold, any increase in the minimum price increases this difference thus leading to an increase in abatement costs. Moreover, cost improvements are guaranteed if at \underline{P} the sufficient conditions holds. \square

For a regulator facing the decision whether to introduce a ETS price floor, the necessary condition in Proposition 2 provides a simple rule to *a priori* ascertain whether such a policy is potentially beneficial. Proposition 2 further suggests that if initially, i.e. before a minimum price is introduced, the ETS permit price is considerably lower than the weighted average of non-ETS prices, the introduction of a ETS price floor chosen sufficiently close to the initial ETS permit price will reduce the abatement costs of achieving a given emissions reduction target. On the other hand, a reduction in abatement costs due to a minimum ETS permit price is possible for cases in which the sufficient condition in Proposition 2 does not hold—provided \underline{P} is not too large.⁷

We have so far been silent on the choice of the distribution parameters ϕ_r . How should one optimally allocate the abatement decrease across counties in the non-ETS partition? Intuitively, countries with the highest MACs should receive the largest shares. Taking the derivative of the change in total abatement cost in (4) with respect to ϕ_r yields:

$$(6) \quad \frac{d\left(\frac{d\Psi}{dP_T}\right)}{d\phi_r} = -P_{Nr} - \phi_r \frac{dP_{Nr}}{d\phi_r}.$$

If MACs do not depend on the level of abatement, equation (6) would only comprise the first term. Then, the country with the highest MAC of all countries in the non-ETS partition should receive the whole share. The abatement cost, however, would fall once the quantity of abatement decreases. The impact on the non-ETS carbon price is reflected through the first and second term: the first term gets smaller (in absolute level) as the country receives a larger share of the distribution while the second term weakens the total cost decrease. If the MAC of the country with the highest marginal cost falls down to that of the country with the second highest marginal cost, the ϕ_r for these two countries is set such that the MACs are equal between the two countries. This process continues until the total abatement decrease for the non-ETS partition has been distributed.

In principle, assuming that the regulator knows the MACs of all firms, it would be possible to choose \underline{P} and ϕ_r to implement the first-best solution under partitioned environmental regulation, thus equalizing MACs across all countries in the non-ETS partition and between both partitions.⁸ In reality, the regulator most likely does not possess information about firms' MAC when choosing \underline{P} and ϕ_r ; rather, it is conceivable that the regulator could rely on simple (but sub-optimal)

⁷Without additional assumptions on the exact shapes of the MAC curves, it is not possible to further qualify these statements. In Section IV, we thus employ numerical analysis that is based on empirical MAC curves to derive additional insights.

⁸This may require setting $\phi_r < 0$ and $\phi_r > 1$ for some countries while still satisfying $\sum_r \phi_r = 1$.

rules to determine ϕ_r (e.g., based on emissions or abatement before the introduction of \underline{P}). We will investigate the effect of introducing a minimum price on total abatement costs under such rules by means of numerical analysis in Section IV.

D. The role of pre-existing fiscal distortions

Price-based pollution control in sectors that are already subject to pre-existing distortionary taxes creates additional efficiency costs due to adverse tax interaction effects (for example, [Bovenberg and Mooij, 1994](#); [Goulder, 1995](#)).⁹ As introducing a minimum price changes the carbon prices in both partitions, it also affects the way how the climate policy interacts with pre-existing fiscal distortions in each partition. For example, if tax distortions are significantly bigger in one partition as compared to the other, assessing the effect on abatement cost from shifting carbon abatement between partitions by means of a minimum ETS price requires taking into account the efficiency impacts due to tax distortions.

To illustrate how pre-existing tax distortions affect the conditions under which the introduction of a price floor decreases total abatement costs, let the additional (public) country- and sector-specific costs caused by tax interaction effects (relative to private abatement costs) be represented by the parameter $\alpha_{ir} \geq 0$.¹⁰ Public abatement cost are then given by: $(1 + \alpha_{ir}) C_{ir} \geq C_{ir}$.

Analogous to the steps for deriving the expression (5)¹¹, one can derive a similar expression for an economy with pre-existing distortions according to which the introduction of a ETS minimum price \underline{P} in an economy with pre-existing fiscal distortions decreases total abatement costs if:

$$(7) \quad \underbrace{\int_{P_T^0}^{\underline{P}} \frac{\partial A_T}{\partial P_T} \left[P_T - \sum_r \phi_r P_{Nr} \right]}_{\text{MAC effect}} + \underbrace{\sum_r \left[\alpha_{Tr} \frac{\partial A_{Tr}}{\partial P_T} P_T - \alpha_{Nr} \phi_r \frac{\partial A_T}{\partial P_T} P_{Nr} \right]}_{\text{Tax interaction effect}} dP_T < 0.$$

Based on expression (7), one can derive necessary and sufficient conditions similar to those stated in Proposition 2 that differ only by including the second term, labelled “Tax interaction effect”, in expression (7).¹² Two important insights

⁹Carbon regulation decreases demand for carbon-intensive intermediate inputs such as refined oil. If these commodities are already taxed, the tax base and thus government revenues are decreasing. As a result, private and public marginal cost differ.

¹⁰For simplicity, we rule out here the possibility of negative tax interaction effects which can occur in the case of pre-existing subsidies on polluting commodities. In this case, the expositions below could be extended straightforwardly.

¹¹With fiscal distortions α_{ir} , equation (3) is replaced by $\frac{\partial \Psi}{\partial \underline{P}_T} = \sum_r ((1 + \alpha_{Tr}) \frac{\partial A_{Tr}}{\partial P_T} P_T - (1 + \alpha_{Nr}) \phi_r \frac{\partial A_T}{\partial P_T} P_{Nr})$.

¹²For $\alpha_{ir} = 0$, $\forall i, r$, condition (7) reduces to (5).

emerge. First, under more general conditions, i.e. when taking into account pre-existing fiscal distortions, the necessary and sufficient conditions in Proposition 2 may not hold anymore. Introducing a minimum ETS permit price may then not necessarily lead to a decrease in total abatement costs if the MAC in the non-ETS partition are larger than the MAC in the ETS partition. Condition (7) shows that the cost reductions from shifting abatement between the two partitions (see “MAC effect”) have to be weighed against the change in abatement costs caused by affecting the tax interaction effects (see “Tax interaction effect”).

Second, if tax interaction effects are relatively small in the non-ETS sector (i.e., “low” α_{Nr} and “high” α_{Tr}), then introducing a binding price floor for ETS permits yields additional efficiency costs as shifting abatement from the ETS to the non-ETS partition means that the increase in tax-interaction costs from a higher ETS carbon price outweighs the savings in tax-interaction costs in the non-ETS partition due to lower non-ETS prices. If, on the other hand, tax interaction effects are relatively large in the non-ETS sectors, then this would constitute an additional economic rationale for introducing a minimum price in the ETS partition. Indeed, there exist high taxes on private transportation fuels in Europe; as transportation fuels make up a large share of EU’s CO₂ emissions while not being covered under the EU ETS, it is important to consider these tax interaction effects when analyzing the impact of a minimum price for EU ETS permits.

II. Quantitative Empirical Framework

To quantitatively investigate the implications of introducing a minimum price into the EU ETS in an empirical context, our subsequent analysis draws on a multi-country multi-sector numerical general equilibrium model of the European economy. Three main reasons motivate our setup. First, it enables us to characterize the (change in) abatement costs for different sectors and countries within and outside of the EU ETS as being determined by technology and price-based market interactions. Second, our framework permits a fully-fledged general equilibrium analysis of tax interaction effects arising from different pre-existing sector- and country-specific taxes in Europe (going beyond the simplistic “reduced-form” representation based on the α s above). Third, we can systematically investigate the role of ϕ_r , i.e. the cross-country distribution of the total abatement decrease in the non-ETS partition, for total abatement costs of the envisaged EU CO₂ emissions reductions when a price floor for EU ETS permits is considered.

The remainder of this section provides an overview of the data, the structure and key features of the numerical general equilibrium model, and our calibration procedure. Additional material is provided in Appendix A containing a complete algebraic description of the model’s equilibrium conditions.

A. Data

This study makes use of a comprehensive energy-economy dataset that features a consistent representation of energy markets in physical units as well as detailed

Table 1. Sectoral and regional detail of numerical general equilibrium model

Sectors ($i \in I$)	
<i>subject to EU ETS</i>	Energy-intensive sector (EIS), Refined oil products (P_C), Electricity (ELE), Air transport (ATP)
<i>outside of EU ETS</i>	Coal (COA), Natural gas (GAS), Crude oil (CRU), Water transport (WTP) Other transport (OTP), Agricultural products, Services (SER), Rest of industry (ROI), Final private consumption, Investment Government consumption
Regions ($r \in R$)	Germany (DEU), France (FRA), Italy (ITA), United Kingdom (GBR), Austria (AUT), Belgium (BEL), Denmark (DNK), Finland (FIN), Greece (GRC), Ireland (IRL), Luxembourg (LUX), Netherlands (NLD), Portugal (PRT), Spain (ESP), Sweden (SWE), Czech Republic (CZE), Hungary (HUN), Malta (MLT), Poland (POL), Romania (ROU), Slovakia (SVK), Slovenia (SVN), Estonia (EST), Latvia (LVA), Lithuania (LTU), Bulgaria (BGR), Cyprus (CYP)

accounts of regional production and bilateral trade. Social accounting matrices in our hybrid dataset are based on data from version 9 of the Global Trade Analysis Project (GTAP) (Narayanan, Badri and McDougall, 2015). The GTAP9 dataset provides consistent global accounts of production, consumption, and bilateral trade as well as consistent accounts of physical energy flows and energy prices.

Table 1 details the regional and sectoral dimensions of the model. We aggregate the GTAP dataset to 28 regions representing the 27 European countries as separate regions and an aggregate “Rest of the World” (ROW) region. We identify 12 commodity groups with specific detail on five energy supply and conversion sectors separating various fuels (natural gas, coal, crude oil) and secondary energy supply (electricity and refined oils) and on other energy-intensive industries. Our choice of sectoral aggregation is guided by the considerations to separately identify sectors which supply primary energy, are large in terms of economic size, exhibit a high energy-intensity, or are subject to the EU ETS. Three final demand sectors represent private and government consumption, and investment demand.

Based on the GTAP data, our model further includes value-added taxes, import tariffs by commodity, sector-specific output taxes and subsidies, and energy-related taxes including mineral oil taxes. Primary factors in the dataset include labor and capital.

B. Model overview

PRODUCTION TECHNOLOGIES AND FIRM BEHAVIOR.—In each industry, gross output is produced using primary inputs of labor, capital, and domestically produced or imported intermediate inputs. We employ constant-elasticity-of-substitution (CES) functions to characterize the production systems. All industries are characterized by constant returns to scale. The nesting structure for each production sector is depicted in Figure A1, Panel (b), in the Appendix A.

Given input prices gross of taxes, firms maximize profits subject to the tech-

nology constraints. Minimizing input costs for a unit value of output yields unit cost indexes (marginal cost). Firms operate in perfectly competitive markets and maximize their profits by selling their products at a price equal to marginal costs. Fossil fuel resources and power technology capital are treated as sector-specific and in fixed supply, whereas capital and labor are treated as perfectly mobile across sectors but assumed to be immobile across regions.

PREFERENCES AND HOUSEHOLD BEHAVIOR.—Given goods and factors prices, a representative household in each region maximizes utility by allocating income, received from government transfers and supplying factors, to consumption. The preferences of the representative household are represented by a CES utility function of consumption goods (see Figure A1, Panel (a), in the Appendix A). At the top level, the composite of energy commodities trades off with the composite of non-energy commodities. At the lower level, energy commodities are combined in one nest, whereas non-energy commodities are combined in the other. Labor supply and savings are assumed to be fixed.

BI-LATERAL TRADE, GOVERNMENT, AND INVESTMENT.—All goods, except for aggregate goods for final private, public, and investment demands are tradable. Bilateral international trade by commodity type is represented following a standard [Armington \(1969\)](#) approach where like goods produced at different locations (i.e., domestically or abroad) are imperfect substitutes. Furthermore, imports from different countries of European Union (and the ROW) are also regarded as imperfect substitutes.

In each region, a single government entity approximates government activities at all levels (national, state, and local). The government collects revenues from factor and commodity taxation and from international trade taxes. Public revenues are used to finance government spending and transfers to households. Aggregate government consumption and transfers to households is represented by a Leontief composite and is financed by tax and tariff revenues. Like government consumption, the composite investment good is modeled using a fixed coefficient production function.

Investment demand and the foreign account balance are assumed to be fixed in real terms.

C. Forward calibration and computational strategy

FORWARD CALIBRATION—The economic effects of introducing a price floor on EU ETS permits depend critically on the baseline conditions for the European economy. Thus, to enhance the policy relevance of our counterfactual computational experiments, we infer the baseline structure of the European economy for 2020 in our comparative-static framework adopting the following, two-stage procedure.

We first calibrate the model such that it replicates the 2011 regional European economies as portrayed by historic GTAP9 data for this year. We use prices and quantities from the integrated economy-energy data set to calibrate the value

share and level parameters following the standard approach in applied general equilibrium modeling (as described, for example, in [Rutherford \(1998\)](#)). Response parameters in the functional forms which describe production technologies and consumer preferences are determined by exogenous elasticity parameters. Table A3 in the appendix lists the substitution elasticities and assumed parameter values in the model. Household elasticities are adopted from [Paltsev et al. \(2005\)](#); [Narayanan, Badri and McDougall \(2015\)](#) provides Armington elasticities and substitution elasticities for the value-added bundle. The remaining elasticities are own estimates consistent with the relevant literature.

In a second step, we do a forward calibration of the 2011 economy to the target year 2020, employing country-level forecasts for GDP growth.¹³ Regional GDP forecasts are based on the *World Economic Outlook 2015* of the International Monetary Fund ([IMF, 2015](#)); energy demands and emissions projections are taken from the “Current Policies Scenario” in the *World Energy Outlook 2015* published by the International Energy Agency ([2015](#)).

COMPUTATIONAL STRATEGY.—Based on [Mathiesen \(1985\)](#) and [Rutherford \(1995\)](#), we formulate the model as a mixed complementarity problem (MCP). We formulate the model as a system of nonlinear inequalities and represent the economic equilibrium through two classes of conditions: zero profit and market clearance. The former class determines activity levels and the latter determines price levels. In equilibrium, each of these variables is linked to one inequality condition: an activity level to an exhaustion of product constraint and a commodity price to a market clearance condition. Importantly, the complementarity-based formulation of our numerical model enables us to endogenously represent corner solutions in equilibrium; for example, as will become evident below, it is important to account for the possibility of “unbinding” national (non-ETS) carbon markets with zero carbon prices. Numerically, we use the General Algebraic Modeling System (GAMS) software and the higher-level language MPSGE ([Rutherford, 1999](#)) and the PATH solver ([Dirkse and Ferris, 1995](#)) to solve the MCP problem.

III. Counterfactual Analysis: A Possible EU Climate Policy Design with a Minimum EU ETS Price?

The design of our counterfactual analysis is guided by examining the effects from introducing a minimum permit price into the EU ETS. Table 2 presents an overview of the counterfactual experiments.

We first consider two scenarios without a minimum price that serve as reference cases. The scenario labelled FULL_TRADING represents the “idealized” policy option in which all emissions sources would be covered under an ETS (which in our setting corresponds to a uniform carbon tax). The scenario CURRENT represents the existing regulatory CO₂ emissions control scheme which consists of the EU ETS and the additional measures enacted at the country level that cover

¹³A similar forward calibration procedure has been used, for example, in [Böhringer and Rutherford \(2002\)](#).

Table 2. Overview of counterfactual experiments

Scenario	Partitioned regulation	Abatement reallocation between ETS and non-ETS partition ($d A_{Nr} = -\phi_r d A_T$)	
		Regional distribution (ϕ_r)	
CURRENT	Yes	–	–
FULL_TRADING	No	Yes	endogenous
MIN_NO	Yes	No	–
MIN_EMISSIONS	Yes	Yes	proportional to emissions
MIN_ABATEMENT	Yes	Yes	proportional to abatement

emissions from the non-ETS sectors.

Emissions reduction targets in the scenario CURRENT reflect the official EU climate policy targets as agreed upon under the *Effort Sharing Decision* under the *Climate & Energy Package* (EU, 2009). Based on this, the country-specific reduction targets for the non-ETS partition, denoted by τ^0 , are shown in Table 3. As these targets are formulated relative to 2005 emissions levels, denoted by E_{rN}^0 , we need to express them relative to our projected, no-climate policy emissions values for 2020, which are denoted by \bar{E}_{rN} . The reduction target for the non-ETS partition for country r relative to the projected level of year-2020 emissions (expressed in percentage terms) is given by:

$$\bar{\tau}_r = 100 \times (1 - \tau_r^0/100) \frac{E_{rN}^0}{\bar{E}_{rN}}.$$

Table 3 reports values for $\bar{\tau}_r$ alongside with historic and projected emissions by country and by partition.¹⁴ Emissions in the ETS partition have to be reduced by 21% by 2020 relative to the level of emissions in 2005. As the year-2005 and projected year-2020 in the ETS sectors are similar, the reduction target expressed relative to 2020 levels is similar, too.

The remaining set of scenarios introduces a minimum price on EU ETS permits (while assuming throughout that regional targets $\bar{\tau}_r$ have to be met). For each minimum price scenario, we consider different levels for the price floor. If the price floor is binding, and given the assumption of an overall constant emissions reduction targets across both partitions, the abatement target in the non-ETS partition is relaxed. The minimum price scenarios differ with respect to whether and how the decrease in abatement is distributed across countries in the non-ETS partition.¹⁵ To isolate the impact of introducing a minimum EU ETS price,

¹⁴While the EU Commission expects all countries to have positive reductions in 2020 relative to a no-policy baseline, some countries in our model—based on the projections for GDP and energy efficiency improvements that underly our forward calibration—exhibit reductions targets close to zero or even negative. We assume a lower bound for $\bar{\tau}_r$ of five percent.

¹⁵The distribution of the abatement between sectors within a given national non-ETS partition is endogenously determined through a national ETS.

Table 3. Baseline country-level CO₂ emissions and reduction targets for non-ETS sectors

	CO ₂ emissions (in million metric tons)						Reductions targets for non-ETS sectors (in %) relative to emissions in year	
	Historic year-2005 values			Projected year-2020 values without climate policy ^a				
	Total	ETS (E_{rT}^0)	Non-ETS (E_{rN}^0)	Total	ETS (\bar{E}_{rT})	Non-ETS (\bar{E}_{rN})	2005 ^b (τ^0)	2020 ^c ($\bar{\tau}_r$)
Austria	79.4	32.1	47.3	76.7	32.2	44.6	16.0	10.9
Belgium	124.3	48.8	75.6	115.6	42.2	73.4	15.0	12.4
Bulgaria	50.3	37.7	12.6	61.5	46.8	14.7	-20.0	5.0
Croatia	23.5	10.6	12.9	22.1	9.0	13.1	-11.0	5.0
Cyprus	7.9	2.8	5.0	7.5	2.8	4.7	5.0	5.0
Czech Rep.	126.2	89.3	36.8	133.2	94.8	38.3	-9.0	5.0
Denmark	51.2	25.5	25.7	49.7	22.4	27.3	20.0	24.6
Estonia	16.4	11.2	5.2	24.2	15.7	8.6	-11.0	32.3
Finland	56.5	35.9	20.6	59.9	35.5	24.4	16.0	29.0
France	421.6	124.2	297.4	400.4	122.2	278.2	14.0	8.1
Germany	861.7	480.3	381.4	904.0	517.8	386.2	14.0	15.1
Greece	112.9	34.5	78.4	102.1	28.8	73.3	4.0	5.0
Hungary	59.9	27.9	32.0	59.1	24.2	34.9	-10.0	5.0
Ireland	47.6	26.2	21.4	46.9	24.5	22.4	20.0	23.5
Italy	488.1	235.8	252.2	417.0	194.7	222.2	13.0	5.0
Latvia	7.7	2.7	5.0	10.7	3.5	7.2	-17.0	18.3
Lithuania	14.0	7.2	6.8	18.9	8.7	10.2	-15.0	23.9
Luxembourg	12.1	4.1	8.0	13.4	4.4	8.9	20.0	28.5
Malta	2.7	2.3	0.4	3.4	2.8	0.6	-5.0	28.2
Netherlands	175.9	87.2	88.7	183.3	84.5	98.8	16.0	24.6
Poland	318.4	215.1	103.2	431.8	274.4	157.4	-14.0	25.2
Portugal	69.2	35.1	34.2	52.8	26.4	26.5	-1.0	5.0
Romania	99.3	63.9	35.3	111.0	69.4	41.6	-19.0	5.0
Slovakia	41.9	24.5	17.4	47.2	24.6	22.6	-13.0	12.9
Slovenia	16.7	8.1	8.6	17.9	8.2	9.7	-4.0	7.9
Spain	365.5	183.3	182.1	308.7	150.0	158.7	10.0	5.0
Sweden	53.2	19.0	34.2	58.3	19.0	39.2	17.0	27.7
UK	558.1	261.5	296.6	554.0	256.0	298.0	16.0	16.4
EU	4262.3	2137.0	2125.3	4291.1	2145.5	2145.7	10.0	13.1

Notes: The ETS target relative to the “no-policy” reference projection in 2020 is 20.9%. ^aBased on forward calibration as described in Section II.C. ^bBased on official EU climate policy targets (EU, 2009). ^cOwn calculations based on official 2005 targets and projected emissions without climate policy.

i.e. without redistribution abatement across partitions, we assume that the abatement target of the non-ETS partition is unchanged (scenario MIN_NO)

In contrast, the scenarios MIN_EMISSIONS and MIN_ABATEMENT assume that the increase in abatement in the ETS partition triggered by a binding minimum price is fully reallocated to the non-ETS partition to meet the overall EU emissions reduction target (i.e., $dA_{Nr} = -\phi_r dA_T$). We consider two cases. In the scenario MIN_EMISSIONS, the abatement decrease is distributed in proportion to baseline emissions:

$$\phi_r = \bar{E}_{rN} / \sum_{r'} \bar{E}_{r'N}.$$

Thus, the larger a country’s baseline emissions, the larger the decrease of the abatement target in the non-ETS sectors. In MIN_ABATEMENT, we assume that the abatement decrease is proportional to abatement targets before introducing the minimum EU ETS price—thus reflecting the agreement among EU Member States under the *Effort Sharing Decision* (EU, 2009):

$$\phi_r = (1 - \bar{\tau}_r/100)\bar{E}_{rN} / \left(\sum_{r'} (1 - \bar{\tau}_{r'}/100)\bar{E}_{r'N} \right).$$

Lastly, to investigate the role of tax interaction effects, we consider two additional scenarios. MIN_NOTAX involves a re-calibrated benchmark economy in 2020 where all distortionary taxes have been removed. MIN_NOOILTAX considers only removing the tax on refined oil (which is used as an intermediate input for other production sectors and final consumption, including private transportation).

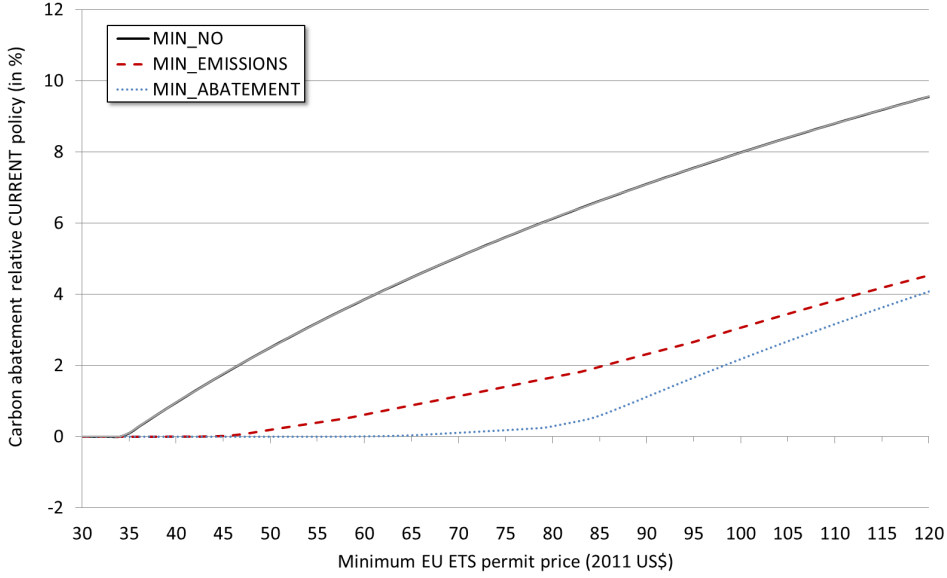
IV. Results

We first focus on examining the aggregate (EU-wide) efficiency consequences of introducing a minimum price into the EU ETS. We then discuss the distributional impacts across countries and finally perform a systematic sensitivity analysis based on a Monte Carlo simulation.

A. Higher price, lower costs? Minimum prices in the EU ETS

CARBON ABATEMENT AND PRICES.—Figure 2 reports the changes in CO₂ emissions abatement for cases without (MIN_NO) and with (MIN_EMISSIONS and MIN_ABATEMENT) a redistribution of the abatement target between the ETS and non-ETS partitions for alternative levels of the minimum ETS price. First, it is important to gauge what level of a potential minimum EU ETS price would constitute a binding constraint; all minimum prices below this threshold then do not change the outcome relative to the CURRENT EU ETS policy (and are hence of no further interest for our analysis). This threshold level is given by the ETS permit price under the CURRENT policy and is \$35.5 per ton CO₂ (see Table 4).¹⁶ Accordingly, for minimum prices lower or equal to the threshold level, the aggregate EU-wide carbon abatement are equal to the abatement under the CURRENT policy amounting to 17% (relative to a “no-climate policy” reference benchmark). As minimum prices increase above the threshold, the minimum constraint becomes increasingly binding and abatement sharply increases as long as it is not offset by a corresponding decrease in abatement in the non-ETS partition (see MIN_NO scenario in Figure 2).

¹⁶As our numerical model is calibrated using base-year data that is denominated in US\$ for 2011, all cost and price numbers throughout the paper are expressed in 2011 US\$.

Figure 2. EU-wide CO₂ abatement for ETS and non-ETS sectors (in %) relative to CURRENT policy

Second, a full redistribution of the increase in abatement in the EU ETS to the non-ETS partition does, however, not necessarily imply that the overall environmental target is unchanged. While low minimum prices above the threshold level (i.e., ≤ 45) yield the same aggregate abatement as under CURRENT policy, the abatement increases for a sufficiently high minimum price level. The reason is that the decrease of the non-ETS abatement targets creates over-abatement for some countries which makes some of the national non-ETS carbon markets “unbinding” (i.e., higher abatement than carbon permit supply) with ensuing zero carbon prices.

Table 4, columns MIN_EMISSIONS and MIN_ABATEMENT, illustrate such outcomes for the case of an optimal minimum price (\$63 and \$75 per ton CO₂, respectively). If the decrease in abatement from the ETS partition is redistributed among the non-ETS sectors based on abatement (MIN_ABATEMENT), the increase in overall abatement is somewhat lower for intermediate minimum EU ETS prices as compared to a redistribution based on emissions (MIN_EMISSIONS). As the former distribution rule assigns relatively high decreases in target levels to countries which already exhibit relatively high abatement levels, over-allocation is less likely as compared to the latter distribution rule. This is also reflected by the lower non-ETS carbon prices under MIN_ABATEMENT when compared to MIN_EMISSIONS.

To summarize, introducing a sufficiently large and binding minimum price into the EU ETS thus entails the possibility of over-achieving the EU-wide emissions

Table 4. Carbon abatement and carbon prices for national carbon markets and EU ETS under current policy and with an optimal minimum ETS price for alternative distribution schemes ϕ_r

	CURRENT	MIN_EMISSIONS	MIN_ABATEMENT
Carbon abatement in EU (in % relative to "no-climate policy" benchmark)	17.0	17.8	17.2
Carbon prices (2011\$/ton CO ₂)			
<i>EU Emissions Trading System (ETS partition)</i>			
Permit price	34.5	63.0*	75.0*
<i>National carbon markets (non-ETS partition)</i>			
Austria	88.5	0.7	0
Belgium	86.2	16.1	7.2
Bulgaria	14.1	0	0
Croatia	25	0	0
Cyprus	4.9	0	0
Czech Republic	16.8	0	0
Denmark	248.8	143.5	32
Estonia	314.2	215.4	56.4
Finland	641	388.5	78
France	61.2	0	4.3
Germany	156.1	47.6	9
Greece	8.5	0	0
Hungary	29.2	0	0
Ireland	304.3	162.4	37.6
Italy	36	0	0
Latvia	128.3	59.3	14.9
Lithuania	216.6	115.5	23.5
Luxembourg	282.3	171.2	35
Malta	363.8	205.5	40.7
Netherlands	247.7	138.3	28.1
Poland	140.5	66.9	11
Portugal	31.9	0	0
Romania	17.4	0	0
Slovakia	62.8	12.4	2.3
Slovenia	53.1	0	2.2
Spain	37.7	0	0
Sweden	574.8	362.3	89.2
United Kingdom	126.7	46.6	13.1
<i>Weighted average of national non-ETS carbon prices</i>			
ϕ_r based on emissions	117.7	43.7	—
ϕ_r based on abatement	110.3	—	9.3

Notes: *Denotes the optimal, i.e. welfare-maximizing, minimum price given the respective redistribution scheme.

reduction target. Since a cost-effectiveness (efficiency) argument requires holding the environmental outcome fixed, this is important to bear in mind when investigating the welfare effects of introducing a minimum price.¹⁷

AGGREGATE WELFARE IMPACTS.—From the necessary condition stated in Proposition 2 we know that introducing a minimum EU ETS price only lowers the

¹⁷In addition, over-abatement implies that the costs of achieving EU emissions reduction goals could be lowered by adopting alternative redistribution schemes that would prevent over-abatement in the non-ETS partition.

Table 5. Aggregate (EU-level) welfare impacts^a for different minimum EU ETS price levels and alternative redistribution schemes ϕ_r

	Minimum EU ETS price (2011\$/ton CO ₂)					
	< 35	40	50	75	90	110
FULL_TRADING	-0.73	—	—	—	—	—
CURRENT	-0.96	—	—	—	—	—
MIN_NO	-0.96	-1.00	-1.07	-1.25	-1.35	-1.49
MIN_EMISSIONS	-0.96	-0.89	-0.82	-0.80	-0.86	-0.98
MIN_ABATEMENT	-0.96	-0.88	-0.77	-0.68	-0.75	-0.92

Note: ^aThe aggregate welfare change refers to the sum of the equivalent variation over countries as is expressed as a percent relative to EU income under no policy.

welfare costs of achieving a given emissions reduction target if the ETS permit price is below the weighted average of regional non-ETS carbon prices before the price floor is imposed. Comparing the ETS and non-ETS prices under CURRENT policy in Table 4—117.3 and 110.3 if weights are based on emissions and abatement, respectively, relative to 34.5—suggests that the potential efficiency gains from introducing a minimum price are substantial.

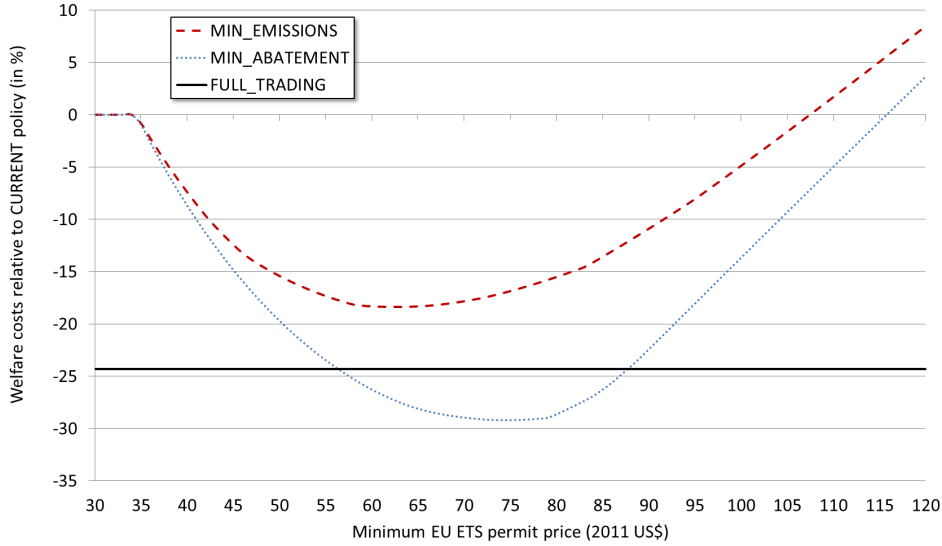
Table 5 reports the aggregate EU welfare impacts for different minimum EU ETS price levels and alternative redistribution schemes ϕ_r . The efficiency loss due to partitioned environmental regulation, i.e. segmented carbon markets, under CURRENT policy relative to a hypothetical FULL_TRADING case is 32%.

For minimum prices lower than \$35 per ton CO₂, the price floor is not binding and hence has no impact. If the price floor binds and the increase in abatement in the ETS partition is not shifted to the non-ETS partition (MIN_NO case), welfare costs increase with higher minimum prices reflecting increasing costs of achieving higher abatement targets. If the overall EU-wide environmental target is held constant, a binding minimum ETS permit price decreases the abatement in the non-ETS partition. Then, a binding minimum price reduces the efficiency loss by shifting abatement from high to low MAC options.

Figure 3 shows the efficiency gains relative to CURRENT policy. First, efficiency gains can be substantial, i.e. up to 30%. Importantly, relatively small price floors around 40-50 \$ per ton of CO₂ are sufficient to yield relatively sizable welfare improvements on the order of 10-25%. Second, the reduction in welfare costs follow a U-shaped pattern: for sufficiently high minimum price levels the welfare improvements get smaller. The reason is that a too high binding minimum price shifts too much abatement to the ETS partition thus failing to exploit relatively low-cost abatement options in the non-ETS partition.¹⁸ This effect is compounded by the issue that with higher minimum prices more national non-ETS carbon markets become non-binding which increases the overall EU-wide abatement. Third, the way in which the abatement decrease in the non-ETS partition is distributed across countries matters. A distribution scheme that

¹⁸For too high minimum prices, the sufficient condition in Proposition 2 does not hold anymore.

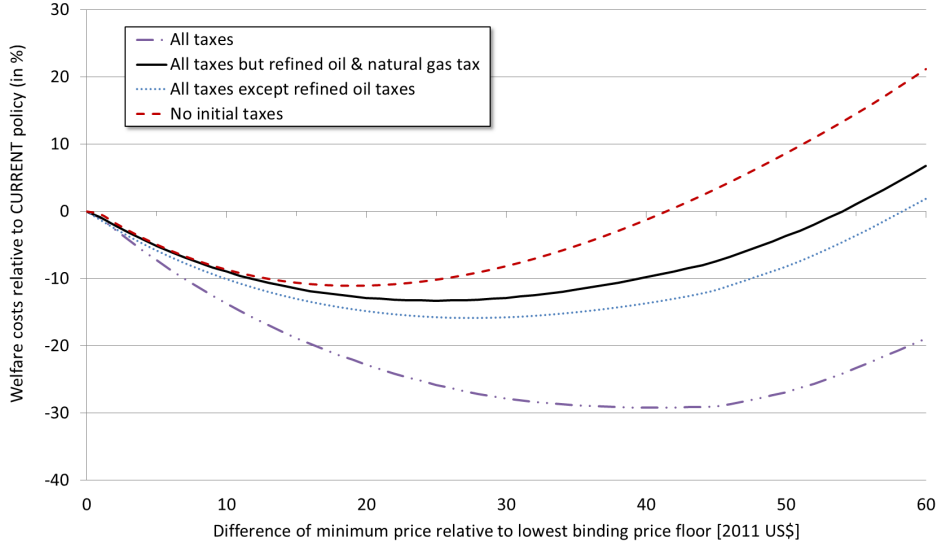
Figure 3. Welfare impacts of introducing a price floor for EU ETS permits



is based on benchmark emissions (MIN_EMISSIONS) entails substantially lower welfare improvements (up to only 20%) as compared to a redistribution based on abatement (MIN_ABATEMENT). The reason is that, everything else equal, a higher abatement share implies higher MACs whereas a higher emission share implies lower MACs. Thus, redistribution based on the Effort Sharing Decision (EU, 2009) (MIN_ABATEMENT) tends to redistribute permits to countries with high abatement targets, i.e., high abatement cost and leads to higher decrease of efficiency cost.

Figure 3 also shows the CURRENT policy would be about 25% more costly than a uniform carbon pricing policy (FULL_TRADING). An important finding is that introducing a minimum ETS permit price under partitioned environmental regulation can achieve the same overall emissions reduction target at lower welfare costs as compared to the case of uniform carbon pricing. For minimum price levels in the range of \$65-85 per ton CO₂, the welfare costs of achieving the same environmental target with a minimum price regulation are of comparable magnitude or may even be lower than under FULL_TRADING. Obviously, such an outcome would not be possible in a first-best setting without pre-existing tax distortions. With the existence of pre-existing tax distortions, however, the introduction of a minimum price—as is reflected by condition (7)—not only improves efficiency by narrowing the difference in MAC across both partitions (“MAC effect”) but also lowers welfare costs by reducing adverse tax interaction effects (“Tax interaction effect”).

Figure 4. Impact of pre-existing tax distortions on welfare costs of introducing a minimum ETS permit price



Notes: All cases shown above assume a redistribution scheme that is based on abatement.

B. Decomposing efficiency gains: how important are tax interaction effects?

How much of the (aggregate) efficiency gains from introducing a minimum ETS permit price are due to the “MAC effect” and the “Tax interaction effect”? And which specific pre-existing tax distortions are mainly responsible for the efficiency gains?

Figure 4 summarizes our insights derived from additional analysis aimed at decomposing the sources of efficiency gains of introducing a minimum ETS price. To gauge the contribution of tax interaction effects, we compare the welfare gains of introducing a minimum price relative to CURRENT policy for different economies which differ by the size of the pre-existing tax distortions. “All taxes” represents the base case model with all tax distortions present (as based on the GTAP9 dataset (Narayanan, Badri and McDougall, 2015) and the calibrated model, see Section II); we then successively remove the refined oil tax, the tax on natural gas, and the other, remaining taxes.¹⁹ For each situation with different tax distortions in place, we compare the welfare costs of the CURRENT policy and with different levels of the minimum price (i.e., we do not compare costs across different tax

¹⁹To determine which taxes are most influential, we have, starting from a situation with all taxes, removed one tax at a time. We only report results for the refined oil and gas taxes here as these turn out to be the single most important tax distortions; all other taxes are removed at once “together” (i.e., moving from “All taxes but refined oil & natural gas tax” to “No initial taxes”). In addition, we have also varied the sequence in which we remove each tax distortion to check for path dependencies.

Table 6. Tax distortions by fuel by partition: size of tax bases and tax rates

	Coal		Natural gas		Refined oil	
	ETS	Non-ETS	ETS	Non-ETS	ETS	Non-ETS
Tax base (bill. 2011\$)	60	3	104	83	525	722
Ad-valorem tax rate ^a (%)	-0.5	29.2	3.7	34.2	20.5	57.3

Notes: Based on version 9 of the Global Trade Analysis Project (GTAP) data (Narayanan, Badri and McDougall, 2015). ^aWeighted average of country- and sector-specific fuel use taxes.

distortions as the benchmark cost under CURRENT policy differ). The horizontal axis shows the difference of the minimum price relative to the lowest binding price floor that is associated with a given situation of tax distortions.²⁰

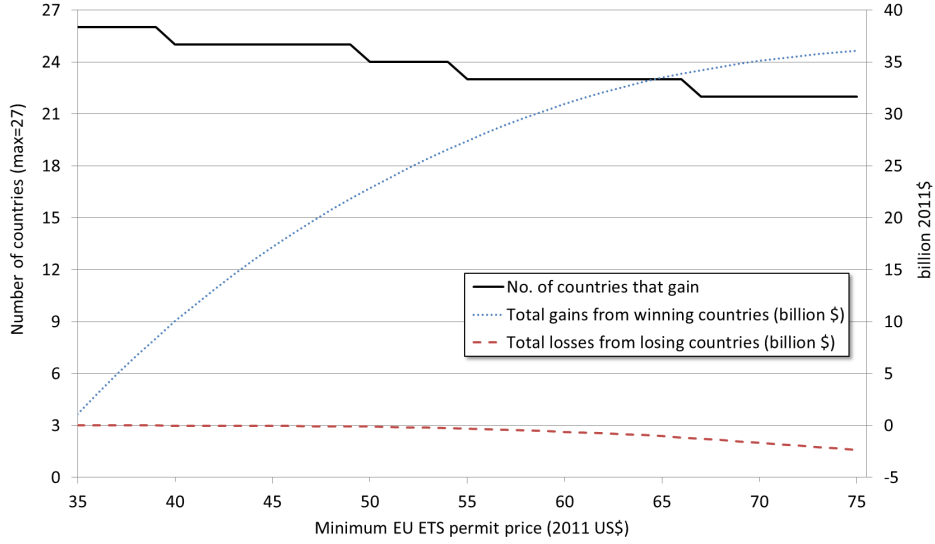
Figure 4 bears out two main insights. First, tax interaction effects are a main driver of the efficiency gains obtained by introducing a minimum ETS permit price. Without any pre-existing tax distortions, the efficiency gain is reduced to a maximum of about 10 percent compared to up to 30 percent for the case with all taxes. Second, the size of efficiency gains due to avoiding adverse tax interaction effects—comparing “All taxes” to “No taxes”—increases more than proportionally with the level of the minimum price.²¹ Second, efficiency gains due to the tax interaction effects mainly hinge on the pre-existing distortions introduced by the refined oil tax and the natural gas tax: the patterns of efficiency gains for different levels of minimum prices are most similar for “All taxes” and “All initial taxes except refined oil & natural gas taxes”. The effect is virtually identical for small minimum prices; for larger minimum prices tax distortions associated with other taxes become increasingly more important.

Table 6 drives home the point that the relative importance of the pre-existing tax distortions associated with refined oil and natural mainly depends on the size of the respective tax base and tax rates for each fuel in each partition. The major bulk of refined oil consumption occurs within the transport sector which is not included in the EU ETS; in addition, the refined oil tax rate in the ETS partition is 2.8 times higher than in the non-ETS partition. Natural gas is taxed at a significantly larger rate in the ETS than in the non-ETS partition although the tax base is relatively larger in the ETS sector. Thus, for both fuels, there exist relatively large tax distortions in the non-ETS partition. Introducing a minimum price shift abatement towards the ETS partition, in turn reducing the efficiency losses in the non-ETS partition as the carbon tax on fuels that are already subject to relatively high taxes is lowered. Although the tax rate on coal in the non-ETS sector is sizeable, its impact on efficiency is negligible due to its small tax base (similar effects are obtained for other pre-existing taxes which are not shown

²⁰This normalization thus helps to focus on the efficiency gains from introducing a *binding* minimum price by controlling for differences in the lowest minimum price which in turn depends on the size of the pre-existing tax distortions.

²¹This is not surprising given that the deadweight loss of taxation is non-linearly increasing in the tax level.

Figure 5. Number of countries with welfare gains, total gains, and total losses due to introduction of minimum EU ETS permit price



here).

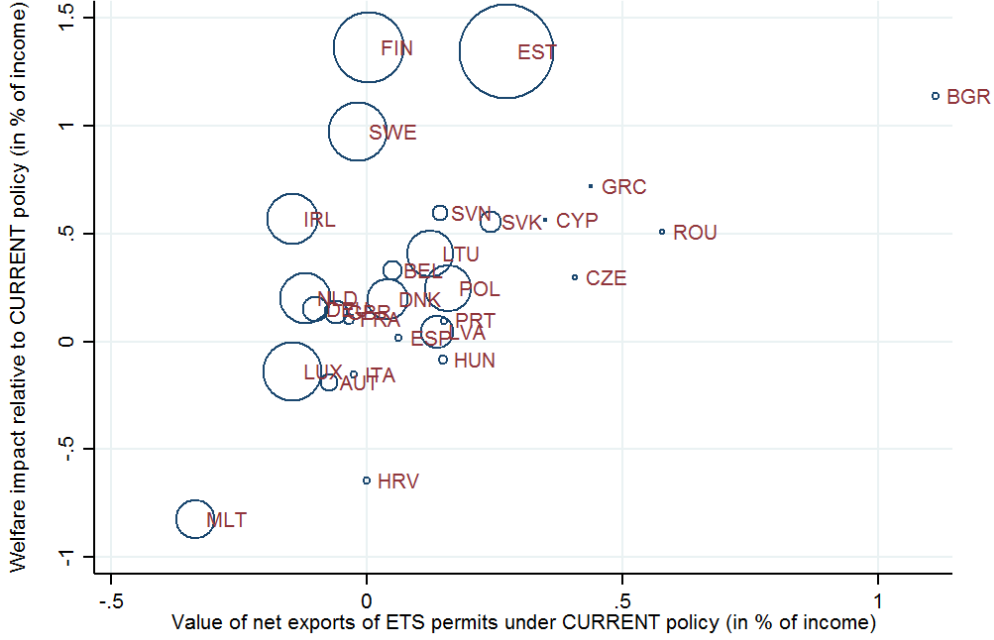
C. Distributional impacts by country

Our analysis suggests that introducing a minimum EU ETS permit price is likely to reduce the aggregate (EU-wide) costs achieving a given emissions reduction target. An important issue from a regional perspective is how the efficiency gain would be distributed among the EU Member States. Importantly, the efficiency argument for introducing a minimum ETS permit price would be strengthened if most countries are better off—or if the impacts on regional equity are relatively small.

Figure 5 reports the number of countries that gain from introducing a minimum price and compares the total gains and losses for winning and losing countries. It is evident that introducing a minimum ETS permit price entails welfare gains for most countries. For moderate minimum price levels below \$50 per ton of CO₂, the price floor is welfare-improving for 24 or more of the 27 countries; for minimum prices above \$75, still 22 countries are better off. In addition, the size of gains vastly exceeds the losses (e.g., by more than \$35 billion per year for a minimum price of \$75). Assuming that appropriate inter-regional transfer mechanisms within the EU exist, it would thus seem feasible to create an outcome which entails gains for all countries.

Why do most countries gains and what explains the losses for some countries? Figure 6 plots on the vertical axis the country-level welfare impacts. The horizontal axis shows the value of net exports of ETS permits under the CURRENT

Figure 6. Country-level welfare impacts of introducing an optimal minimum ETS price



Notes: The optimal minimum ETS price here refers to the price floor that minimizes aggregate (EU-wide) welfare costs of meeting the given reduction target under a redistribution scheme that is based on abatement. The size of the bubbles indicates the MAC in the non-ETS partition under CURRENT policy multiplied by the redistribution share, $P_r^N \phi_r$, and measured relative to benchmark income.

policy. An increase in the ETS permit price increases (decreases) the gains from permit trade for countries which are net exporters (importers) of permits. The size of the bubbles indicates the savings in abatement costs which are approximated by the term $P_r^N \phi_r$ measured relative to benchmark income: *ceteris paribus* savings are the larger, the larger are the non-ETS MACs under CURRENT policy, P_r^N (see Table 4), and the larger is the abatement decrease allocated to country r , ϕ_r .

The followings insights emerge from Figure 6. First, there is a positive relationship between the value of net permit trade and the welfare impact of a country. Countries which are relatively large net exporters of ETS permits, gain more from introducing a minimum ETS permit price. The majority of countries which are net importers are worse off (Italy, Austria, Luxembourg, and Malta).

Second, the net permit trade position of a country does not fully predict the sign of its welfare impact: a number of countries experience (small) welfare gains although they are net ETS permit importers (Germany, France, Netherlands, Ireland, and Sweden). The explanation is that these countries experience relatively large reductions in their abatement costs in the non-ETS sectors induced

by shifting away emissions abatement from the non-ETS partition (indicated by relatively large bubble sizes). As these countries exhibit a high share of abatement in the non-ETS partition under CURRENT policy, they absorb a relatively large fraction of the total abatement decrease in the non-ETS partition (high ϕ_r). In addition, these countries are characterized by relatively high MAC in their non-ETS sectors (high P_r^N). For example, Sweden and Finland experience the largest welfare gains of all countries as they display the highest non-ETS carbon prices under CURRENT policy (see Table 4).

D. Robustness checks: size of the optimal minimum price and maximum welfare gains?

Given the considerable uncertainty surrounding our parametrization of production and consumption technologies—and in turn implicit MAC in each sector and country—in the numerical general equilibrium model, we perform systematic sensitivity analysis to check for the robustness of our results.

To this end, we perform a Monte Carlo analysis assuming that each parameter (as displayed in Table A3) is uniformly distributed with upper and lower support equal to 0.5 and 1.5 times its central case value, respectively.²² For each draw, we simulate the CURRENT policy scheme, representing current EU climate policy, and compute the optimal minimum price level which maximizes aggregate EU welfare.²³ This enables us to characterize both (1) the distribution of the maximum welfare gains attainable by introducing a minimum ETS permit price and (2) distribution of optimal price floors that would implement such gains.

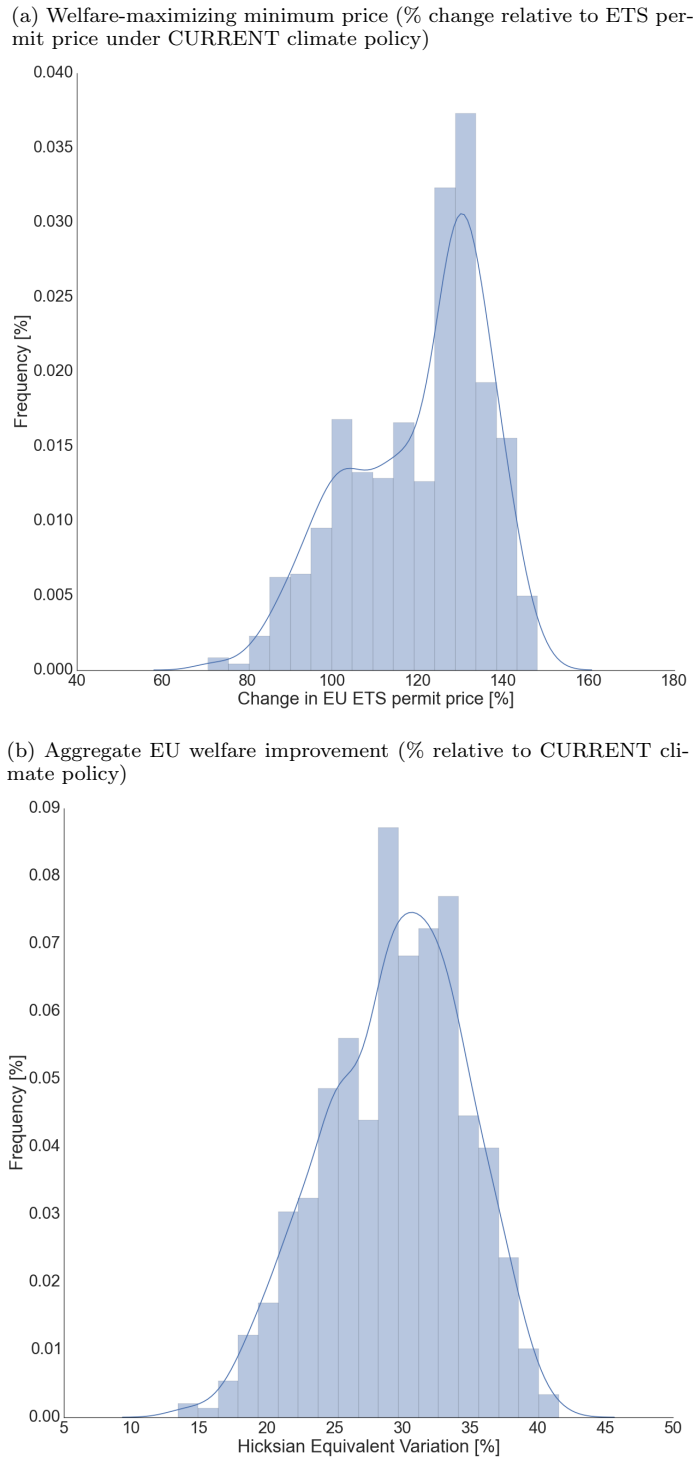
How large is the optimal minimum EU ETS permit price and how big are potential welfare gains? If the regulator sets too low a price floor, the policy is ineffective; a policy with a too high price floor forgoes potential efficiency gains—or may even result in welfare losses relative to a situation without a minimum price (compare with Figure 3). Figure 7a shows the distribution of the welfare-maximizing minimum price expressed as a % change relative to ETS permit price under the CURRENT policy; Figure 7b shows the corresponding distribution of the aggregate welfare gains for optimal minimum prices. Figure 7a provides information about the lower and upper values of the optimal price floor and the associated welfare gains: an *optimal* minimum price in the range of 70 to 150 % of the EU ETS price under current EU climate policy will (1) not produce a welfare loss and (2) yield aggregate welfare gains between 15 and 40%.

Importantly, as the regulator is arguably uncertain about firms' MACs when deciding on the minimum price level, it is not possible to precisely set the optimal minimum price. Hence, the welfare improvements associated with non-optimal minimum prices are likely to be smaller than those shown in Figure 7b. Nonetheless, our systematic sensitivity analysis suggests that our finding of sizeable welfare

²²These distributional assumptions are driven by the lack of estimates in existing studies on the empirical (joint) distributions of our model parameters.

²³We assume here that the abatement decrease in the non-ETS partition is distributed in proportion to abatement.

Figure 7. Distribution of optimal minimum price and welfare gains due to introduction of minimum EU ETS price



gains from introducing a minimum EU ETS price under partitioned environmental regulation is robust.

V. Concluding remarks

This paper has examined whether and by how much the abatement costs of achieving a given environmental target under partitioned climate regulation that is majorly based on an international ETS can be reduced by introducing a minimum price for ETS permits. We have theoretically characterized the conditions under which a price floor for ETS permits brings about welfare gains by reducing the differences in marginal abatement costs (MAC) across the partitions of environmental regulation. We have shown that a higher ETS permit price does not have to increase compliance costs of achieving a given environmental target: total abatement costs are reduced if MAC across countries and sectors in the non-ETS partition are on average higher than the minimum ETS price. Importantly, this is precisely the situation of European carbon abatement where the MAC in non-ETS sectors in most countries are substantially higher than those in ETS sectors.

To quantitatively assess the aggregate and country-level distribution of welfare gains of introduction a minimum price in the EU ETS, we have applied a numerical multi-country multi-sector general equilibrium model of the European carbon market. We find that low to moderate ETS price floors on the order of \$50-70 per ton of CO₂ can reduce the welfare costs of achieving EU climate policy targets by 20-30 percent relative to current policy. Welfare gains are driven by a decrease in the difference of MAC between firms in the ETS and non-ETS partition and a reduction in negative tax interaction effects as abatement is shifted away from non-ETS sectors that are subject to high pre-existing fuel taxes. Importantly, we find that the cost of reducing CO₂ emissions with an effective minimum price policy are close, and can even be lower, than what would be realized under uniform carbon pricing, i.e. in the absence of partitioned environmental regulation. The efficiency argument for a minimum price in the EU ETS is strengthened by our finding that the likely distributional impacts among the EU Member States do not adversely affect regional equity: most EU Member States are better off with the gains of winning countries vastly exceeding the losses of losing countries. Systematic sensitivity analysis for optimal minimum price policies shows that our results are robust with respect to parametric uncertainty in production and consumption technologies.

An important premise of our analysis is that the environmental target always has to be fulfilled and that the regulator can implement a mechanism which adjusts the sectoral targets based on ex-post abatement costs. Such a mechanism may in practice, for example, be implemented sequentially by adjusting the targets in each period based on observed, past prices and abatement quantities. In fact, the Market Stability Reserve (MSR)—to be introduced in Phase 4 of the EU ETS—will adjust the supply of permit in each year based on observed excess

supply (demand). While the MSR mechanism could be conceived as effectively altering the environmental target, our premise is that the number of allowances is preserved over time. Our analysis therefore provides an economic argument for an allowance-preserving MSR-like mechanism that focuses on increasing the cost-effectiveness of partitioned environmental regulation by narrowing the difference in MAC between the ETS and the non-ETS partition.

While our analysis contributes to the discussion of cost-effective policy designs for EU climate policy, several directions for future research appear fruitful. First, while we assume that emissions in the non-ETS sector are regulated in a cost-minimizing manner, the question of instrument choice and design in the non-ETS partition, and potential interactions with (optimal) hybrid ETS policies, could be further investigated. In particular, this would also enhance the realism of our analysis in light of the existing “patchwork” of regulatory climate policy instruments in many European countries. Second, extending our analysis to a dynamic setting would enable investigating intertemporal aspects such as banking and borrowing and dynamic cost-effectiveness of emissions trading systems. Another line of important future research would be to consider optimal hybrid policy designs when firms themselves are subject to uncertainty when deciding about, for example, investments in production capacity and future abatement technology.

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APPENDIX A: EQUILIBRIUM CONDITIONS FOR NUMERICAL GENERAL EQUILIBRIUM MODEL

We formulate the model as a system of nonlinear inequalities and characterize the economic equilibrium by two classes of conditions: zero profit and market clearance. Zero-profit conditions exhibit complementarity with respect to activity variables (quantities) and market clearance conditions exhibit complementarity with respect to price variables.²⁴ We use the \perp operate to indicate complementarity between equilibrium conditions and variables. Model variables and parameters are defined in Tables A1, A2, and A3.

Zero-profit conditions for the model are given by:

$$\begin{array}{llll}
 \text{(A1)} & c_r^C \geq PC_r & \perp & C_r \geq 0 & \forall r \\
 \text{(A2)} & c_{ir} \geq PY_{ir} & \perp & Y_{ir} \geq 0 & \forall i, r \\
 \text{(A3)} & c_r^G \geq PG_r & \perp & G_r \geq 0 & \forall r \\
 \text{(A4)} & c_r^I \geq PI_r & \perp & I_r \geq 0 & \forall r \\
 \text{(A5)} & c_{ir}^A \geq PA_{ir} & \perp & A_{ir} \geq 0 & \forall i, r \\
 \text{(A6)} & c_i^T \geq PT_i & \perp & T_i \geq 0 & \forall r
 \end{array}$$

where c denotes a cost function. According to the nesting structures shown in Figure A1b, the expenditure function for consumers is defined as:²⁵

$$c_r^C := \left[\theta_r^{CON} (c_r^{CENE})^{1-\sigma^{ctop}} + (1 - \theta_r^{CON}) (c_r^{CCON})^{1-\sigma^{ctop}} \right]^{\frac{1}{1-\sigma^{ctop}}}$$

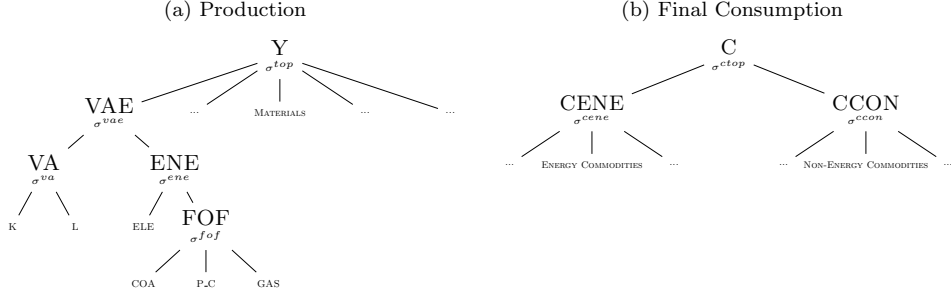
where

$$c_r^{CENE} := \left[\sum_{i \in cene} \theta_{ir}^{CENE} \left(\frac{PAE_{ir}}{pae_{ir}} \right)^{1-\sigma^{cene}} \right]^{\frac{1}{1-\sigma^{cene}}}$$

²⁴A characteristic of many economic models is that they can be cast as a complementary problem, i.e. given a function $F: \mathbb{R}^n \rightarrow \mathbb{R}^n$, find $z \in \mathbb{R}^n$ such that $F(z) \geq 0$, $z \geq 0$, and $z^T F(z) = 0$, or, in short-hand notation, $F(z) \geq 0 \perp z \geq 0$.

²⁵Prices denoted with an upper bar generally refer to baseline prices observed in the benchmark equilibrium. θ generally refers to share parameters.

Figure A1. Nested Structure for Production and Consumption



$$c_r^{CCON} := \left[\sum_{i \in ccon} \theta_{ir}^{CON} \left(\frac{PAE_{ir}}{\overline{pae}_{ir}} \right)^{1-\sigma^{ccon}} \right]^{\frac{1}{1-\sigma^{ccon}}},$$

and where PAE_{ir} denotes the tax inclusive Armington prices defined as:²⁶ $PAE_{ir} := (1 + t_{ir}) PA_{ir}$.

Unit cost functions for production activities are given as:

$$c_{ir} := \left[\sum_{j \in mat} \theta_{jir}^{ytop} \left(\frac{PAE_{jr}}{\overline{pae}_{jr}} \right)^{1-\sigma^{top}} - \left(1 - \sum_{j \in mat} \theta_{jir}^{ytop} \right) (c_{ir}^{VAE})^{1-\sigma^{top}} \right]^{\frac{1}{1-\sigma^{top}}}$$

where

$$c_{ir}^{VAE} := \left[\theta_{ir}^{VAE} (c_{ir}^{VA})^{1-\sigma^{vae}} + (1 - \theta_{ir}^{VAE}) (c_{ir}^{ENE})^{1-\sigma^{vae}} \right]^{\frac{1}{1-\sigma^{vae}}}$$

$$c_{ir}^{VA} := \left[\theta_{ir}^{VA} \left(\frac{(1 + t_{ir}) PL_r}{\overline{pl}_{ir}} \right)^{1-\sigma^{va}} + (1 - \theta_{ir}^{VA}) \left(\frac{(1 + t_{ir}) PK_r}{\overline{pk}_{ir}} \right)^{1-\sigma^{va}} \right]^{\frac{1}{1-\sigma^{va}}}$$

$$c_{ir}^{ENE} := \left[\sum_{j \in ele} \theta_{jir}^{ENE} \left(\frac{PAE_{jr}}{\overline{pae}_{jr}} \right)^{1-\sigma^{ene}} + \left(1 - \sum_{j \in ele} \theta_{jir}^{ENE} \right) (c_{ir}^{FOF})^{1-\sigma^{ene}} \right]^{\frac{1}{1-\sigma^{ene}}}$$

$$c_{ir}^{FOF} := \left[\sum_{j \in fof} \theta_{jir}^{FOF} \left(\frac{PAE_{jr}}{\overline{pae}_{jr}} \right)^{1-\sigma^{fof}} \right]^{\frac{1}{1-\sigma^{fof}}}.$$

For government and investment consumption, fixed production shares are assumed:

²⁶We abstract here from cost for carbon which are added to the price and suppress for ease of notation the fact that taxes are differentiated by agent.

$$c_r^G := \sum_i \theta_{ir}^G \frac{PAE_{ir}}{\overline{pae}_{ir}}$$

$$c_r^I := \sum_i \theta_{ir}^I \frac{PAE_{ir}}{\overline{pae}_{ir}}.$$

Trading commodity i from region r to region s requires the usage of transport margin j . Accordingly, the tax and transport margin inclusive import price for commodity i produced in region r and shipped to region s is given as: $PM_{irs} := (1 + te_{ir})PY_{ir} + \phi_{jirs}^T PT_j$. te_{ir} is the export tax raised in region r and θ_{jirs}^T is the amount of commodity j needed to transport the commodity. The unit cost function for the Armington commodity is:

$$c_{ir}^A := \left[\theta_{ir}^A PY_{ir}^{1-\sigma^{dm}} + (1 - \theta_{ir}^A) (c_{ir}^M)^{1-\sigma^{dm}} \right]^{\frac{1}{1-\sigma^{dm}}}$$

where

$$c_{ir}^M := \left[\sum_s \theta_{is}^M \left((1 + tm_{ir}) \frac{PM_{is}}{\overline{pm}_{is}} \right)^{1-\sigma^m} \right]^{\frac{1}{1-\sigma^m}}.$$

International transport services are assumed to be produced with transport services from each region according to a Cobb-Douglas function:

$$c_i^T := \prod_s PY_{is}^{\theta_{is}^T}.$$

Denoting consumers' initial endowments of labor and capital as \bar{L}_r and \bar{K}_r , respectively, and using Shephard's lemma, market clearing equations become:

$$(A7) \quad Y_{ir} \geq \sum_s \frac{\partial c_{is}^A}{\partial PY_{ir}} A_{is} + \frac{\partial c_i^T}{\partial PY_{ir}} T_i \quad \perp \quad PY_{ir} \geq 0 \quad \forall i, r$$

$$(A8) \quad A_{ir} \geq \sum_j \frac{\partial c_{jr}}{\partial PA_{ir}} Y_{jr} + \frac{\partial c_r^C}{\partial PA_{ir}} C_r + \frac{\partial c_r^G}{\partial PA_{ir}} G_r + \frac{\partial c_r^I}{\partial PA_{ir}} I_r \quad \perp \quad PA_{ir} \geq 0 \quad \forall i, r$$

$$(A9) \quad \bar{L}_r \geq \sum_i \frac{\partial c_{ir}}{\partial PL_r} Y_{ir} \quad \perp \quad PL_r \geq 0 \quad \forall r$$

$$(A10) \quad \bar{K}_r \geq \sum_i \frac{\partial c_{ir}}{\partial PK_r} Y_{ir} \quad \perp \quad PK_r \geq 0 \quad \forall r$$

$$(A11) \quad T_i \geq \sum_{j,r} \frac{\partial c_{jr}^A}{\partial PT_i} A_{jr} \quad \perp \quad PT_i \geq 0 \quad \forall r$$

$$(A12) \quad I_r \geq \bar{i}_r \quad \perp \quad PI_r \geq 0 \quad \forall r$$

$$(A13) \quad C_r \geq \frac{INC_r^C}{PC_r} \quad \perp \quad PC_r \geq 0 \quad \forall r$$

$$(A14) \quad G_r \geq \frac{INC_r^G}{PG_r} \quad \perp \quad PG_r \geq 0 \quad \forall r.$$

Private income is given as factor income net of investment expenditure and a lumpsum or direct tax

Table A1. Sets, and price and quantity variables

Symbol	Description
<i>Sets</i>	
$i \in I$	Commodities
$r \in R$	Regions
$ccon \subset I$	Non-energy consumption commodities
$cene \subset I$	Energy consumption commodities
$mat \subset I$	Material input commodities
$ele \subset I$	Electricity input commodities
<i>Prices and quantities</i>	
PA_{ir}	Armington price of commodity i in region r
PL_r	Wage rate in region r
PC_r	Consumer price index in region r
PG_r	Public consumption price index in region r
PI_r	Investment consumption price index in region r
G_r	Public consumption index in region r
C_r	Private consumption index in region r
A_{ir}	Armington index of commodity i in region r
INC_r^C	Private income in region r
INC_r^G	Public income in region r
I_r	Investment consumption index in region r
Y_{ir}	Production index sector i in region r
T_i	Production index international transport service i
PT_i	Price index international transport service i
PK_r	Capital rental rate in region r
PY_{ir}	Domestic commodity i output price in region r
PM_{irs}	Price of commodity i import produced in region r and shipped to region s
PAE_{ir}	Tax and carbon cost inclusive Armington price of commodity i in region r

payment to the local government. Public income is given as the sum of all tax revenues:

$$(A15) \quad INC_r^C := PL_r \bar{L}_r + PK_r \bar{K}_r - PI_r \bar{i}_r - htax_r$$

$$(A16) \quad INC_r^G := \sum_i ti_{ir} PA_{ir} \left[\sum_j \frac{\partial c_{jr}}{\partial PA_{ir}} Y_{jr} + \frac{\partial c_r^C}{\partial PA_{ir}} C_r + \frac{\partial c_r^G}{\partial PA_{ir}} G_r + \frac{\partial c_r^I}{\partial PA_{ir}} I_r \right] \\ + \sum_i Y_{ir} \left[tl_r PL_r \frac{\partial c_{ir}}{\partial PL_r} + tk_r PK_r \frac{\partial c_{ir}}{\partial PK_r} \right] \\ + \sum_{i,s} \left[te_{ir} PY_{ir} \frac{\partial c_{is}^A}{\partial PY_{ir}} A_{is} + tm_{ir} (1 + te_{is}) PY_{is} \frac{\partial c_{ir}^A}{\partial PY_{is}} A_{ir} \right] \\ + htax_r.$$

Table A2. Model parameters

Symbol	Description
<i>Elasticity of substitution parameters</i>	
σ_r^{ctop}	Top level consumption (energy vs. non-energy consumption)
σ_r^{cene}	Final consumption energy commodities
σ_r^{ccon}	Final consumption non-energy commodities
σ_{ir}^{top}	Top level (material vs. value added/energy inputs) in sector i
σ_{ir}^{va}	Value added composite in production sector i
σ_{ir}^{vae}	Value added vs. energy composite in production sector i
σ_{ir}^{ene}	Energy composite in production sector i
σ_{ir}^{fof}	Fossil fuels in production sector i
σ_{ir}^{dm}	Domestic vs. imported commodity i
σ_{ir}^m	Imports of commodity i
<i>Other parameters</i>	
i_r	Reference investment level
$htax_r$	Direct tax from household to local government
\overline{pae}_{ir}	Armington price inclusive of reference tax and carbon cost
\overline{pl}_{ir}	Tax-inclusive reference price for labor in production i
\overline{pk}_{ir}	Tax-inclusive reference price for capital in production i
\overline{pm}_{irs}	Tax-inclusive import price commodity i shipped to region s
tl_{ir}	Labor use tax in production i
tk_{ir}	Capital use tax in production i
ti_{ir}	Use tax for commodity i
te_{ir}	Export tax for commodity i
tm_{ir}	Import tax for commodity i
θ_r^{CON}	Expenditure share of energy commodities in total expenditure
θ_r^{CENE}	Expenditure share of commodities i in total energy expenditure
θ_{ir}^{CON}	Expenditure share of commodities i in total non-energy expenditure
θ_{jir}^{ytop}	Share of commodity j in top-level production i
θ_{ir}^{VAE}	Share of value-added cost in value-added/energy cost bundle
θ_{ir}^{VA}	Share of labor cost value added cost bundle in production i
θ_{jir}^{ENE}	Share of commodity j cost in energy bundle in production i
θ_{jir}^{FOF}	Share of commodity j cost in fossil fuel bundle in production i
ϕ_{jirs}^T	Amount of commodity j needed to transport commodity i from r to s
θ_{ir}^G	Expenditure share commodity i public consumption
θ_{ir}^I	Expenditure share commodity i investment consumption

Table A3. Parameter values for substitution elasticities in production and consumption

Parameter	Description	Value
<i>Production</i>		
σ^{YTOP}	Materials vs. energy/value-added bundle	0.20
σ^{YMAT}	Materials	0.30
σ^{KLE}	Value-added vs. energy bundle	0.25
σ^{KL}	Capital vs. labor	0.30-1.50
σ^{ENE}	Primary energy vs. electricity	0.30
σ^{FOF}	Fossil fuels	0.80
<i>Consumption</i>		
σ^{top}	Energy vs. non-energy consumption	0.25
σ^{ene}	Energy commodities	0.40
σ^{oth}	Non-energy commodities	0.50

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