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Kill Bill or Tax: An Analysis of Alternative CO_2 Price Floor Options for EU Member States

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Kill Bill or Tax:

An Analysis of Alternative CO_2 Price Floor Options for EU Member States

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Abstract

Several EU member states are exploring options for setting minimum domestic carbon prices within the EU Emission Trading System (ETS). First, a "*TAX*" policy would introduce a carbon tax equal to the difference between the prevailing ETS price and the targeted minimum price. Second, a national auction reserve price would "*KILL*" allowances by invalidating them until the ETS price equalled the national minimum price. Third, a government could require domestic overcompliance and "*BILL*" covered entities for extra allowances per ton of emissions, thereby increasing demand for allowances and pulling up the ETS price. We explore the implications of these policy options on national and ETS-wide carbon prices, revenues from emissions allowances, emissions, and economic welfare. We find that a national government's preferred unilateral policy will depend on the extent to which it values the fiscal benefits of revenues, which favor *TAX* or to a lesser degree *BILL*, versus climate benefits, which favor *KILL* and also *BILL*, particularly for jurisdictions with more emissions to leverage for overcompliance. Our analysis can be generalized to other multilateral cap-and-trade systems where participants pursue more stringent internal emission pricing through unilateral policies.

Keywords: CO_2 price floor, emissions trading, carbon tax

JEL codes: H23, Q58, D62

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1. Introduction

Between 2008 and 2018, the emissions allowance prices in the European Union's Emissions Trading System (EU ETS) were stuck at very low levels, between €5 and €10 per ton of carbon dioxide (CO_2). Several factors have been blamed, including the financial crisis and ensuing recession (Ellerman et al. 2016), as well as overlapping targets for renewable energy and energy efficiency that exert a downward pressure on allowance prices (Böhringer and Rosendahl 2010). As countervailing measures, the European Commission postponed the auctioning of 900 million allowances until 2019–2020 (so-called back-loading) and introduced a market stability reserve from 2019 onwards (EU 2018), which pushed the allowance price above €20/tCO_2. However, substantial concerns remain about the durability of the effect of these measures in the mid-run (Rosendahl 2019; Flachsland et al. 2019) and the sufficiency of the ETS allowance prices for sustaining the decarbonization path towards climate neutrality by 2050 (Edenhofer et al. 2017; Ricke et al. 2018).

Against this background, several EU member states are exploring options for setting minimum CO_2 prices nationally. Notably, the United Kingdom led by introducing a domestic CO_2 price floor for electricity generators in 2013; initially slated to rise, that price is currently capped at £18/ton (around €20/ton) through 2020. The Netherlands has drafted a law for a minimum CO_2 price in the electricity sector, similar to that in the United Kingdom, and is exploring options for the industrial sectors as well.[1] France in 2016 floated its proposal, which would have set a domestic CO_2 price floor of €30/ton for domestic power plants. Germany is having its own discussions about a price floor for CO_2.[2]

[1] https://www.internetconsultatie.nl/minimumco2prijs
[2] https://www.montelnews.com/en/story/eleven-german-state-ministers-urge-co2-price-floor-/918136

The European Commission has been resistant to the idea of a CO_2 price floor in the EU ETS. In part, this hesitance stems from concerns that a price floor might trigger the special decision rule requiring unanimity in the European Council, which prior to the ETS torpedoed efforts to design an EU-wide CO_2 tax. Legal scholars argue that introducing an auction reserve price into the EU ETS could be done with the ordinary procedure (see Fischer et al. 2020). Still, the European Commission has preferred to rely on quantity-based measures in the form of the market stability reserve (Perino and Willner 2016; Perino 2018).

As a result, member states that wish to ensure minimum CO_2 prices are seeking unilateral options. Three aspects of EU law make this possible. First, Article 193 of the Treaty on the Functioning of the European Union (EU 2012) states that EU legislative acts based on environmental policy shall not prevent the member states "from maintaining or introducing more stringent protective measures." Member states are thus free to impose their own CO_2 taxes. Second, allowances are classified as financial instruments, meaning member states may trade in them, including purchasing and retiring them. Third, member states are allocated specific volumes of the allowances to be auctioned; they may use the common platform to auction them or opt out and appoint their own auction platform. In fact, Germany, Poland, and the United Kingdom have all opted out and taken charge of their own auctions. Thus, member states may have an opportunity to set their own auction rules, such as including a reserve price.[3] To summarize: member states can design unilateral measures to raise CO_2 prices within their jurisdictions and also retire allowances they control.

We evaluate three options for unilateral measures and their consequences for national and ETS system-wide allowance prices, revenues from emissions allowances, emissions, and

[3] That possibility hinges on the interpretation of "shall auction" in the EU ETS auction law, and whether that means to offer allowances for sale or sell them at any clearing price

economic welfare. First, a national minimum price can be implemented by a tax equal to the difference between the prevailing ETS price and the minimum price ("*TAX*"). This policy is effective at raising revenues but results in a "waterbed effect," lowering system-wide allowance prices while emissions remain unchanged under the cap; price disparities across member states induce system-wide efficiency costs. Second, a national auction reserve price raises system-wide prices by withholding allowances ("*KILL*"). This strategy lowers system-wide emissions while maintaining price equalization across jurisdictions; however, only a narrow range of price increases can offset the revenue cost of lost sales for those with a unilateral price floor. A final option would be for participating member states to require domestically covered entities to retire additional allowances for their emissions compliance, so that the effective cost per unit of emissions equals the targeted minimum price ("*BILL*"). This policy has the effect of increasing demand for allowances and thus pushing up the ETS price while reducing system-wide emissions; the price increase is enjoyed by all allowance holders, so revenues increase in proportion to the member states' auctioned allowance holdings; firms in participating jurisdictions face higher marginal abatement costs, leading to a system-wide efficiency loss.

Our theoretical analysis investigates three incentives for unilateral action. First, additional revenues can bring fiscal benefits, such as when they lower other, more distortionary taxes (Goulder 1995), or if earmarking carbon-related revenues offers a more politically acceptable funding source for needed public expenditures towards the low-carbon transition (Baranzini and Carattini 2017; Kallbekken et al. 2011). Second, additional (or displaced) emissions reductions can bring environmental benefits when the prevailing ETS price does not fully internalize the social cost of carbon or ancillary pollutants. Third, changes in the ETS price influence the terms of allowance trade, creating gains or losses if the member state is a significant net importer or exporter of allowances. Each option has somewhat different implications for these different objectives.

For a given domestic minimum price, *TAX* raises the most revenues for the floor-price jurisdiction and results in the lowest system-wide allowance prices—and the largest price differential—but no net reduction in emissions. *KILL* lowers emissions the most and maintains cost-effectiveness but requires the greatest financial sacrifice by the acting jurisdiction. *BILL* represents a compromise between effecting real emissions reductions and retaining revenues, albeit with an efficiency loss due to higher domestic marginal abatement costs.

A numerical simulation model of the EU ETS parameterized to empirical data offers quantitative insights into optimal strategies. Estimates of the marginal cost of public funds for member states indicate that the fiscal benefits of raising revenues from emissions taxes can be considerable, in which case *TAX* can be a preferred policy despite its inability to reduce emissions. On the other hand, if the social cost of carbon is high enough relative to the reference ETS price, *BILL* or *KILL* is preferable. We find that, for comparable emissions reductions, the efficiency loss of *BILL* relative to *KILL* is modest, but the trade cost of *KILL* can become substantial. As a result, *BILL* can be preferable for achieving environmental benefits, and more so when additional weight is given to public revenues. Ultimately, a national government's preferred policy will depend on the extent to which it values revenues, which suggests *TAX* or to a lesser degree *BILL*, versus the scope of emissions reductions, which favors *KILL* and also *BILL*, particularly for jurisdictions with more emissions to leverage for overcompliance in order to absorb more allowances from the emissions cap.

The remainder of this paper is organized as follows. Section 2 provides a theoretical analysis of the economic effects of the three unilateral policy options to achieve domestic minimum prices. Section 3 details our numerical model of the EU ETS calibrated to empirical data. Section 4 presents the quantitative results for a unilaterally acting jurisdiction, and discusses optimal strategies for price floors. Section 5 concludes. Although our analysis has been motivated by environmental policy initiatives of EU member states, the insights may apply more generally to any jurisdictions linked by an emissions trading system.

2. Theoretical analysis

Consider a simple model of an emissions cap-and-trade scheme with two participating jurisdictions, as illustrated in Figure 1. One jurisdiction, *G*, has greater ambition and is considering unilateral action, while the other remains under the cap but is taking no further interventions, indexed by *R*. The overall cap is set at *A* and allocated among the jurisdictions such that $A_R + A_G = A$. Of the jurisdictional allocation, a_i allowances are auctioned (allocated to the government), and the rest ($f_i = A_i - a_i$) are freely granted to firms or installations. The market price of allowances is *p*, and that price prevails in jurisdiction *R*. Jurisdiction *G* may choose a different domestic price p_G. In the reference situation—that is, in the absence of additional unilateral policy—both jurisdictions face the same allowance price, p^{ref}.

Each jurisdiction has covered entities with a marginal willingness to pay (WTP) for emissions that produces a downward-sloping demand curve for emissions $E_i(p_i)$. Let $E_i^0 = E_i(0)$ be baseline emissions without any regulations, and $E_i^{ref} = E_i(p^{ref})$ be reference emissions with the existing cap. For later ease of notation, let $z_i = -\partial E_i / \partial p_i$ ($z_i > 0$) be the slope parameter of the emissions demand curve, which we assume is approximately linear in the range of prices we are considering.

Total abatement costs, $TAC_i(E_i(p_i)-E_i^0)$, are the forgone surplus from reducing emissions from the no-policy baseline (the dark triangle in Figure 1). With price-taking representative firms, *marginal* abatement costs are always equalized with the prevailing domestic emissions price: $TAC_i'(E_i(p_i)-E_i^0)=p_i$. Trade costs (*XC*) are payments for remaining emissions, net of the value of government revenues (*GR*) and private allowance allocations: $XC_i = p_i E_i - GR_i - p(A_i - a_i)$. Since transfers between domestic entities—through tax payments or allowance sales—cancel each other out, the trade costs for the unilaterally acting jurisdiction *G* always equals the value of net imports from *R*: $XC_G = p(A_R - E_R)$.[4] In Figure 1, *G* is represented as a slight net importer of allowances, with trade costs marked by the light rectangle, while for *R*, the light overlapping rectangle represents benefits from net allowance exports. Total *compliance* costs for *G* are thus $TCC_G = TAC_G(E_G(p_G)-E_G^0) + p(A_R - E_R)$.

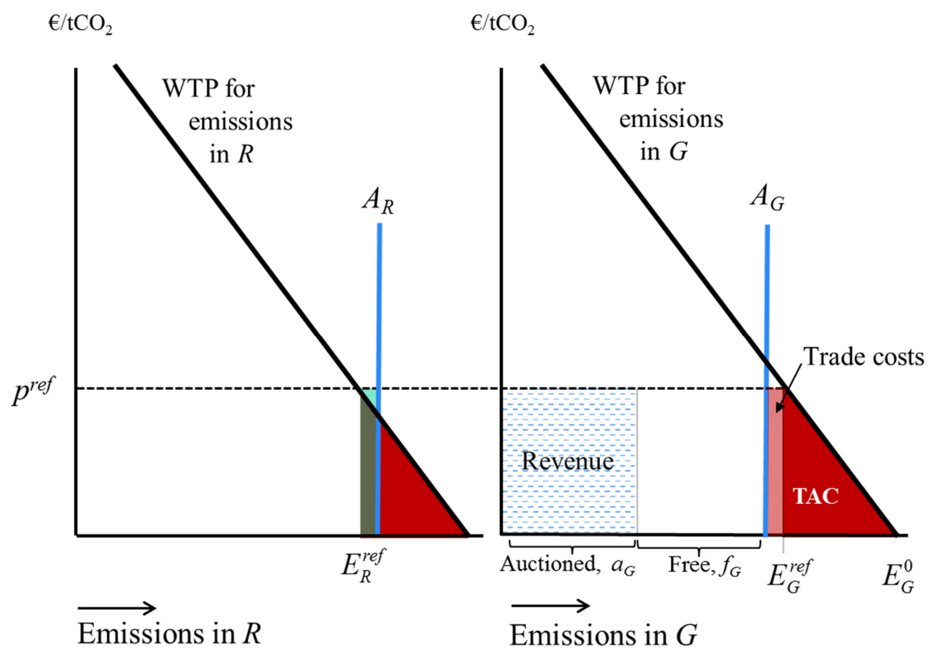
In deciding what domestic price (p_G) it prefers, the jurisdiction with greater ambition takes into account its perceived social cost of emissions, assumed to have a constant marginal damage rate δ; emissions outside the jurisdiction may be discounted (or inflated) by the weight β. For example, conventional pollutants can be more or less damaging if they occur away from home, depending on dispersal, but for climate change the location does not matter ($\beta = 1$). Environmental benefits for *G* of unilateral action are $B_G = \delta\left((E_G^{ref} - E_G) + \beta(E_R^{ref} - E_R)\right)$.

The government may also place an extra weight γ on government revenues relative to the cost borne by domestic firms. For example, a public budget constraint could lead to $\gamma > 0$, if additional revenues could be used to offset more distorting taxes or fund underprovided clean

[4] Note that in scenarios with allowance invalidation, $E_G - A_G$ no longer represents net imports for the unilateral actor, but net exports from the remaining jurisdictions are always representative.

technologies.[5] (See Section 4.3 for further discussion.) Revenues for the reference scenario are $p^{ref}a_G$, as indicated by the patterned rectangle in Figure 1.

Figure 1. Two-jurisdiction model of an ETS without unilateral intervention



By unilateral action (i.e., price floor policies), the government in *G* aims to maximize its potential welfare gains, ΔW_G, compared with the reference situation. It thereby trades off the reduction in perceived environmental damages plus the fiscal benefits of an increase in government revenues (*GR*) against the change in total compliance costs:

$$\Delta W_G = B_G + \gamma\left(GR_G - GR_G^{ref}\right) - (TCC_i - TCC_i^{ref}) \tag{1}$$

The subsequent analysis will focus on the perspective of *G*; only the variables that require distinction from *R* will be subscripted (i.e., the parameters γ, δ, β, etc. are in practice country-

[5] On the other hand, interest-group lobbying could induce policymakers to care more about economic surplus than government coffers, implying $\gamma < 0$.

and region-specific, but the foreign values do not enter into the acting jurisdiction's welfare function, so we drop the indexing).

2.1. TAX: Charging the difference between the floor and ETS price

One option for setting a domestic price floor is to introduce a carbon tax equal to the difference between the prevailing ETS price and the targeted minimum price. The Carbon Price Support mechanism in the United Kingdom (UK) follows this model: the carbon price floor is determined by the price of CO_2 from the EU ETS and the price support rate per ton of CO_2 to make up the difference for the UK-only additional ton of CO_2 emitted in the UK power sector.

This option leads to more emission abatement domestically, but it has well-known deficiencies. One is that it causes marginal abatement costs to diverge across jurisdictions, inducing a system-wide efficiency loss in meeting the overall emissions cap. The other is known as the "waterbed effect": reducing domestic demand for allowances does not change the total number of allowances under the cap but rather drives down the value of tradable allowance and allows the other jurisdictions to emit more under the cap (see, e.g., Böhringer et al. 2008; Fischer and Preonas 2010).

We observe this effect in Figure 2. The acting jurisdiction raises its minimum price to p_G, reducing emissions in G, allowing an equal expansion in R, which lowers the ETS price to p. The combination of higher domestic prices and lower ETS prices also effectively shifts some revenues from R to G.

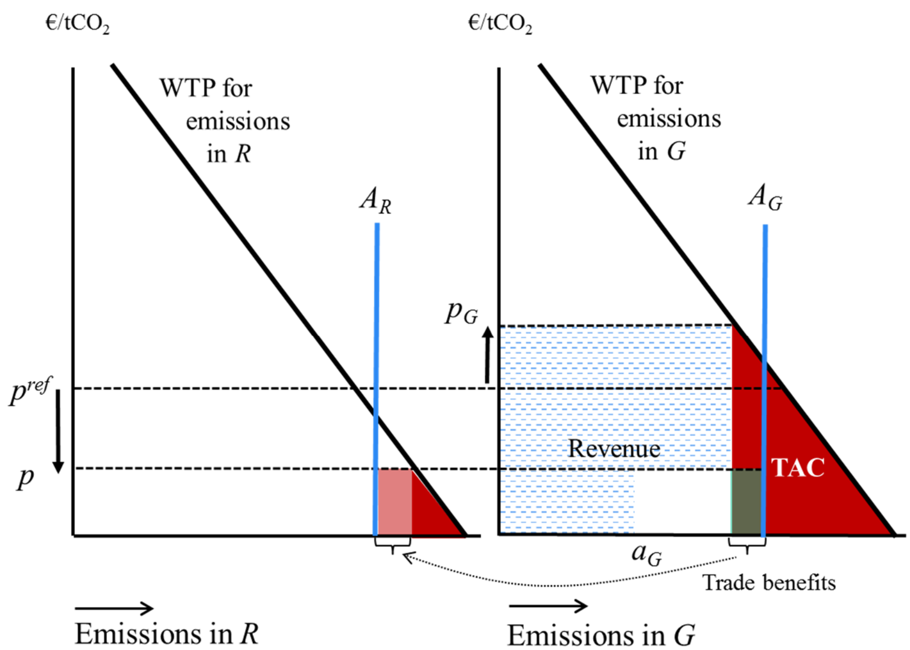
By totally differentiating the cap constraint $A = E_G + E_R$,[6] we find how the unilateral price floor influences the prevailing market price for allowances:

[6] I.e., $dp_G \partial E_G / \partial p_G + dp \partial E_R / \partial p = 0$.

$$\frac{dp}{dp_G} = -\frac{\partial E_G / \partial p_G}{\partial E_R / \partial p} = -\frac{z_G}{z_R} < 0$$

That is, the market price falls according to the ratio of the slopes of the emissions demand curves.

Figure 2. ETS market equilibrium with unilateral carbon tax in *G*



Domestic revenues are the sum of the carbon tax paid by domestic firms plus the auction revenues at the market price: $GR_G^{TAX} = (p_G - p)E_G + pa_G$. Compared with the reference case, the change in total government revenues from the unilateral price floor is then $GR_G^{TAX} - GR_G^{ref} = (p_G - p)E_G - (p^{ref} - p)a_G$. The first term is positive (excluding the possibility of negative emissions), reflecting the emissions tax collections. The second term is negative, reflecting the lost auction revenues. Note that the price gap in the first term is higher than that in the second term. Still, as the domestic price rises, domestic emissions fall. The smaller the jurisdiction's share of allowances in the overall cap, the larger the range in which implementing a domestic price floor will increase revenues.[7]

Since total emissions are fixed, $\partial E_R / \partial p_G = -\partial E_G / \partial p_G$ (i.e., emissions under the cap are simply shifted across jurisdictions in the waterbed-effect) as long as the emissions cap is binding. Environmental benefits of unilateral action are then $B_G^{TAX} = \delta(1-\beta)(E_G^{ref} - E_G)$, which is zero unless marginal damages for *G* are different for different jurisdictions $(\beta \neq 1)$.

Maximizing group welfare with respect to its choice of the domestic price p_G, we set the first derivative equal to zero and solve for the optimal price floor (see Appendix A.1 for the complete derivation). As a result, we see three potential incentives to change the domestic price from the market price, despite the waterbed effect:

$$p_G^{TAX} = p + \underbrace{\frac{\delta(1-\beta)}{1+\gamma}}_{\substack{\text{marginal benefit of} \\ \text{shifting abatement}}} + \underbrace{\frac{\gamma}{1+\gamma}\left(\frac{E_G}{z_G} + \frac{E_G - a_G)}{z_R}\right)}_{\substack{\text{marginal excess benefit of} \\ \text{additional revenues}}} + \underbrace{\frac{(A_R - E_R)}{(1+\gamma)z_R}}_{\substack{\text{marginal benefit of} \\ \text{improving terms of} \\ \text{allowance trade}}} \qquad (2)$$

Under the cap, the prevailing market price reflects the value of emissions abatement. The next term is positive if $\beta < 1$—that is, if abatement is more valuable at home than in *R*. The second bracketed term is positive if $\gamma > 1$—that is, if the government cares more about revenues than about surplus. The last term is also positive if the jurisdiction is a net importer of allowances, since it benefits from the lower cost of purchasing allowances in the market.

[7] That is, revenues will increase until the domestic price premium reaches $p_G^{T\max} - p = E_G / z_G + (E_G - a_G) / z_R$.

2.2. KILL: Withholding from auction or retiring allowances

The second option would avoid the waterbed effect by reducing the supply of allowances. Jurisdiction *G* can decide to withhold (or "kill") *k* permits from auction—or, equivalently, use auction revenues to purchase and retire permits—to achieve the targeted reserve price p_G.

Under this option, both *jurisdictions G* and *R* face the same allowance price, p_G. In equilibrium, under the adjusted cap constraint, $E_G + E_R = A - k$. Thus, if jurisdiction *G* wants to raise the allowance price to p_G, it will need to invalidate $k = A - E_G - E_R$ allowances, so $\partial k / \partial p_G = -\partial E_G / \partial p_G - \partial E_R / \partial p = z_G + z_R$.[8] Because of this invalidation, *KILL* leads to environmental benefits, both from tightening the cap and potentially from emissions shifting: $B_G^{KILL} = \delta\left(k + (1-\beta)(E_R - E_R^0\right)$.

Figure 3 illustrates the effects of the unilateral *KILL* policy. Total compliance costs rise because of both higher abatement costs (dark triangle) and higher net trade costs (indicated rectangle). The trade costs are smaller than the value of the government's unsold permits, since part of the reduction in the government's allocation is offset by private domestic allowances freed for sale by additional reductions. Government revenue is $GR_G^{KILL} = p_G(a_G - k)$, which may be larger or smaller than the reference revenue, depending on whether the unilaterally acting jurisdiction will lose more on the allowances not sold than it will gain on the remaining allowances it sells.[9]

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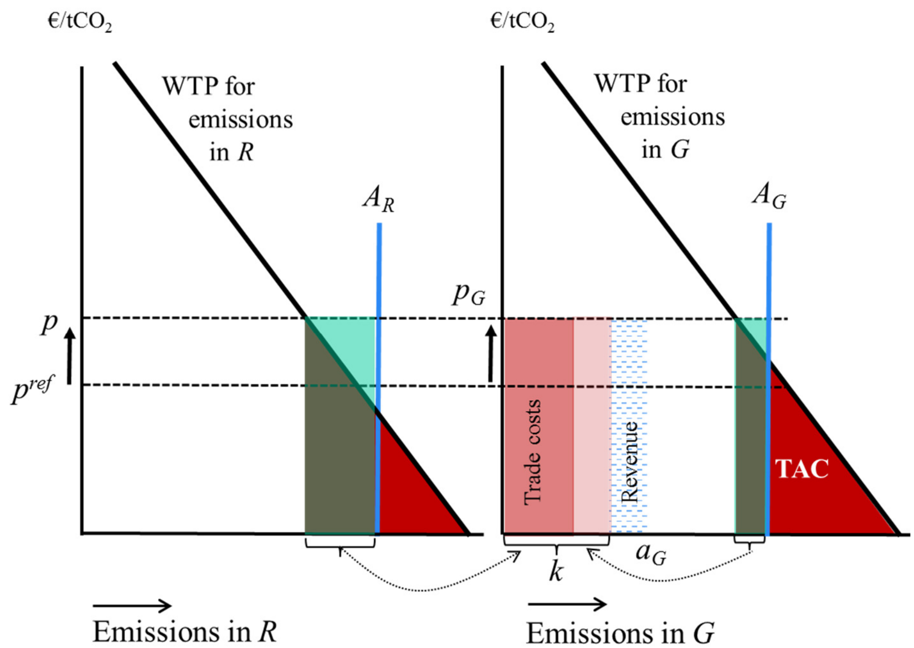
[8] Using our linear functional forms, $k = (p_G - p_0)(z_R + z_G)$, and we see the maximum market price the group can sustain, which involves cancelling its entire allocation from auction, is equal to $p_G^{K\max} = p_0 + a_G / (z_R + z_G)$.

[9] On the margin, $\partial TR_G^{KILL} / \partial p_G = (a_G - k) - p_G(z_R + z_G)$. The revenue-maximizing price floor target for *KILL* is $p_G^{Krev} = (p_0 + a_G / (z_G + z_R)) / 2 = p_G^{K\max} / 2$, or half of the maximum achievable price, with our linear functional

Figure 3. ETS market with unilateral reserve price in *G*



Maximizing welfare gains for the unilaterally acting jurisdiction through the *KILL* strategy, we set the first derivative equal to zero and solve for the strategically optimal reserve price (see Appendix A.2 for full derivations):

$$p_G^{KILL} = \underbrace{\frac{\delta}{1+\gamma}\left(1-\frac{(1-\beta)z_R}{z_G+z_R}\right)}_{\text{marginal benefit of additional abatement}} + \underbrace{\frac{\gamma}{1+\gamma}\left(\frac{a_G-k}{z_G+z_R}\right)}_{\text{marginal excess benefit of additional revenues}} - \underbrace{\frac{(A_R-E_R)}{(1+\gamma)(z_G+z_R)}}_{\text{marginal cost of deteriorating terms of allowance trade}} \tag{3}$$

The first term is the perceived (revenue-adjusted) marginal damage of emissions; this term simply reduces to δ if $\beta = 1$ and $\gamma = 0$. Second, if $\gamma > 0$, there is some added incentive to raise the price and thus the revenues from the remaining auctioned allowances. Third, terms-of-trade effects also matter: note that G would need to be an exporter to benefit from an increase in

forms. The corresponding allowances withheld to maximize revenues are less than half of those available for auction; in this case, $k^{Krev} = (a_G - p_0(z_G + z_R))/2$.

the common allowance price, but it becomes more likely a net importer the more allowances it invalidates.

2.3. BILL: Supplemental compliance requirement

The third option would be to require domestic covered entities to retire more allowances for their compliance; that is, if the desired domestic price floor is p_G but market prices are p, resident covered entities would have to surrender $\phi = p_G / p$ allowances for their emissions.[10] Such compliance ratios do have some precedent: requiring compliance at a ratio other than 1:1 was, for example, part of the Clean Air Interstate Rule in the United States. Figure 4 illustrates the effect on the ETS market of the overcompliance requirement.

A supplemental compliance requirement has the effect of *increasing* demand for allowances, and thus pushing up the ETS price. For the cap to clear with the additional compliance requirement in G, the total number of allowances surrendered must equal the cap: $(p_G / p)E_G + E_R = A.$ Thus, $\phi = (A - E_R) / E_G.$ Equivalently, the excess compliance payments by firms in G must equal the value of the allowances retired: $(p_G - p)E_G = p(A - E_R - E_G)$.

Solving for the resulting market price of allowances, we get $p = p_G E_G / (A - E_R)$. Totally differentiating, considering the response of emissions in both jurisdictions, solving and rearranging (see Appendix A.3.1), we see the response of the ETS price to the *BILL* price floor can be to rise but not to the full extent of the domestic price:

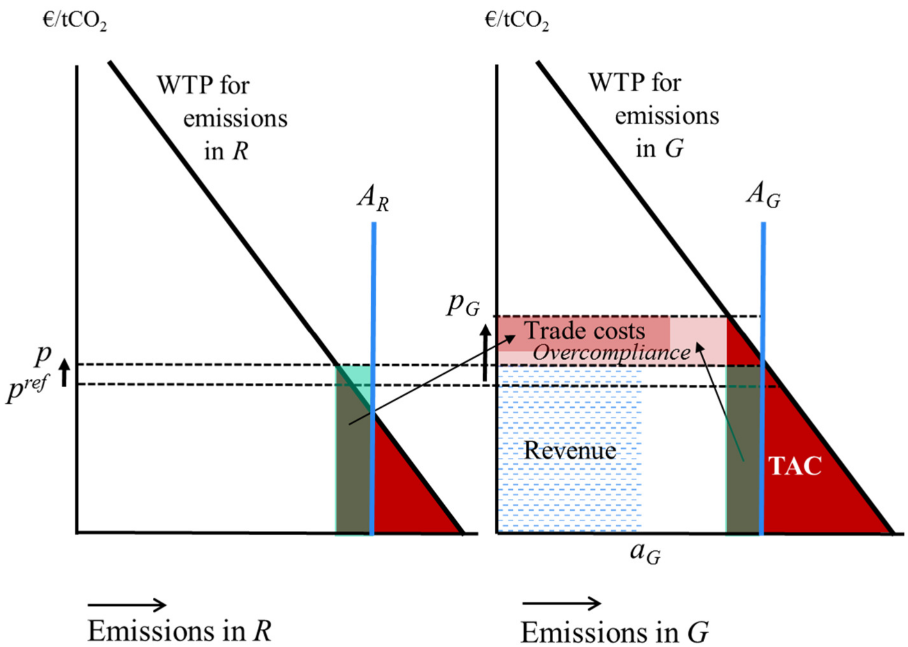
$$\frac{dp}{dp_G} = \frac{\phi\left(1 - p_G z_G / E_G\right)}{\phi^2 + p_G z_R / E_G} < 1$$

[10] Karp and Traeger (2017) propose a variation of a system-wide "smart cap" to address uncertainty; here we consider a regional version to address system-wide overallocation.

We assume that p_0 is low enough that $dp / dp_G > 0$, at least initially.[11]

Note that the acting government does not raise revenues directly from the additional compliance requirement, since those allowances can be purchased anywhere in the market. Government revenues under *BILL* are simply the auctioned allowance value, $GR_G^{BILL} = pa_G$, as shown in the patterned rectangle in Figure 4.

Figure 4. ETS market with unilateral overcompliance requirement in *G*



However, this option entails a system-wide efficiency loss due to the divergence in marginal abatement costs. It requires higher costs for *G*'s industry: although it reduces emissions more, firms must make additional emissions payments, as seen in the overcompliance rectangle in Figure 4. The compliance requirement is equivalent to the jurisdiction's imposing a tax differential and earmarking the revenues to purchase and retire allowances.

[11] More specifically, we assume $p^{ref} << \min[E_G^{ref} / z_G, E_G^{ref} / z_R]$, since at $p_G = p^{ref}$, $A - E_R = E_G$. Above that price, the emissions base in the subgroup is shrinking faster than the additional compliance requirement increases, resulting in a net loosening of the cap.

Trade costs under *BILL* include both net allowance purchases $(p(E_G - A_G))$ and domestic overcompliance costs $((p_G - p)E_G)$, which together with the revised emissions constraint reduce to $XC_G^{BILL} = p(A_R - E_R)$, the value of net allowance imports from *R* (see Appendix A.3.2). These net trade costs are indicated in the medium-dark rectangle in Figure 4. They are less than the total overcompliance costs, since some of the allowance supply feeding the overcompliance requirement is purchased from domestic allowance holders.

Maximizing the welfare change with respect to the domestic price (meaning a compliance ratio of p_G/p (see Appendix A.3.3), we can solve for and express the optimal p_G^{BILL} as

$$p_G^{BILL} = \underbrace{\omega\delta\left(1+\beta\frac{z_R}{\phi z_G}\right)}_{\substack{\text{marginal benefit of}\\ \text{additional abatement}}} + \underbrace{\omega\gamma\frac{a_G}{z_G}}_{\substack{\text{marginal excess}\\ \text{benefit of}\\ \text{additional revenues}}} - \underbrace{\omega\frac{(A_R - E_R)}{\phi z_G}}_{\substack{\text{marginal cost of deteriorating}\\ \text{terms of allowance trade}}}$$

where $\omega = \dfrac{(A - E_R)\phi}{\phi A_G + (E_G - \gamma a_G)z_R / z_G + z_R\delta(\beta\phi - 1)}$. Since *BILL* raises the market price of allowances, benefits arise from the additional emissions reductions, the additional revenues to the government from its auctioned allowances, and potentially from an improvement in the terms of trade, to the extent the acting jurisdiction is a net exporter of allowances.

2.4. Comparing price floor options

From the preceding analysis, we can establish clear ordinal rankings for some of the outcomes.

Proposition 1: *For the same domestic CO_2 price, then* $p^{KILL} > p^{BILL} > p^{ref} > p^{TAX}$ *and* $E^{KILL} < E^{BILL} < E^{ref} = E^{TAX}$.

Proof: By the assumption, all domestic firms face the price p_G. Under *KILL*, p_G also applies to all other firms under the cap; under *BILL*, firms outside the jurisdiction face a lower price than domestic firms, but higher than without the intervention $(p^0 < p < p_G)$; meanwhile, the *TAX* policy drives down allowance prices $(p < p^0)$. The emissions result follows from the CO_2 prices in *R*, implying a reverse ranking for the nonacting jurisdiction's emissions; domestic emissions are held constant across the options, and the cap holds under *TAX*. □

It follows that to achieve the same net emissions, the acting jurisdiction must seek a higher domestic allowance price with *BILL* than with *KILL*, since *R* will be doing less $(p^{BILL} < p_G^{KILL} < p_G^{BILL})$. The *TAX* option cannot achieve lower emissions unless the ETS price is driven to zero, so *R* does no abatement while *G* firms do more than the total abatement implied by the cap.

Proposition 2: *For the same domestic CO_2 price, if the unilaterally acting jurisdiction's emissions exceed its auction allocation, then* $GR_G^{TAX} > GR_G^{BILL} > GR_G^{KILL}$.

Proof: If $E_G - a_G \geq 0$, then $GR_G^{TAX} = p_G a_G + (p_G - p)(E_G - a_G) \geq p_G a_G > a_G p_G / \phi$ $= GR_G^{BILL}$. Furthermore, $GR_G^{BILL} > GR_G^{KILL}$ if $(a_G - k) < a_G / \phi$ or $(\phi - 1)a_G < \phi k$, which we see is true because $(\phi - 1)a_G < (\phi - 1)E_G^{BILL} < k < \phi k$. The first step results from the auction allocation assumption; the second step reflects that the number of allowances withdrawn from overcompliance is less than those withdrawn under the unilateral CO_2 price, following emissions in Proposition 1; the third step notes that $\phi > 1$. □

That the acting jurisdiction's auction allocation is not greater than its emissions is a sufficient but not necessary condition for this ranking to hold. Of course, which policy the jurisdiction will prefer depends on how it weights the different outcomes.

3. Numerical model and data

Our quantitative assessment of CO_2 price floor options is based on numerical simulations with a partial equilibrium model of the EU ETS (see, e.g., Böhringer et al. 2008, 2014). We expand this model for the logic of alternative unilateral CO_2 pricing options (see Appendix B for the detailed model algebra).

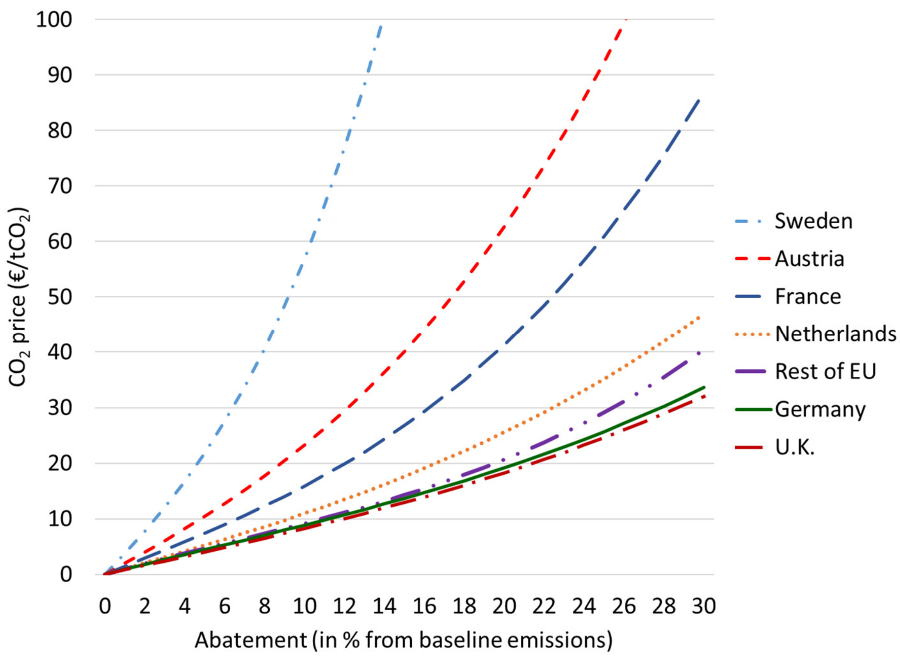
The model builds on jurisdiction-specific nonlinear marginal abatement cost (MAC) curves calibrated to empirical data. To obtain these MAC curves we draw on simulations with an established large-scale, multiregion computable general equilibrium (CGE) model of global trade and energy use (see, e.g., Böhringer et al. 2015) based on the most recent data from the Global Trade Analysis Project (Aguiar et al. 2019) that covers all EU member states with their ETS sectors. We generate MAC curves by a sequence of CGE simulations, with CO_2 prices rising from €0 to €100 per ton of CO_2 in steps of €1. The resulting endogenous emissions reductions in the composite ETS sector for each member state then enter a least-square fit where we match flexible polynomial functions of third degree to the CGE "observations" in CO_2 prices and CO_2 emissions reductions.[12]

In our model parameterization, we explicitly represent the six member states that have been discussing unilateral CO_2 price floors more vividly: Germany, United Kingdom (UK), France, Netherlands, Austria, and Sweden. All other member states are summarized in a composite region (Rest of EU). Figure 5 depicts the MAC curves for the model regions as

[12] The CGE model describes production technologies in industries via nested separable constant-elasticity-of-substitution (CES) cost functions that capture price-responsive substitution possibilities across different inputs. We adopt a standard KLEM nesting of capital inputs (K), labor inputs (L), composite energy inputs (E), and composite material inputs (M). The energy composite further splits into electricity and a CES aggregate of fossil fuels with fuel-specific CO_2 content. Emissions abatement triggered by CO_2 pricing thus takes place by (1) fuel switching, (2) substitution between energy and other inputs (energy efficiency improvements), and (3) output adjustments (energy savings). All these abatement mechanisms are reflected in the MAC curves.

function of the percentage emissions reductions (Table B.2 in Appendix B reports the regression coefficients of the MAC curves).

Figure 5. Marginal abatement cost curves



We calibrate the partial equilibrium model to a reference situation in 2018 with a prevailing EU ETS allowance price of €15/tCO_2. The reference situation is characterized by CO_2 emissions allowances that have been officially allocated to each EU member state that year according to the provisions of the EU ETS.[13] The ETS price of €15 keeps emissions at the allocated EU ETS budget of 1646 mtCO_2. Emissions abatement at €15/tCO_2 amounts in total to 296 mtCO_2, which equals 15.2 percent of the pre-abatement ETS baseline emissions of 1941 mt.[14] Reflecting the differences in MAC curves, (i.e., the ease of substituting away from CO_2

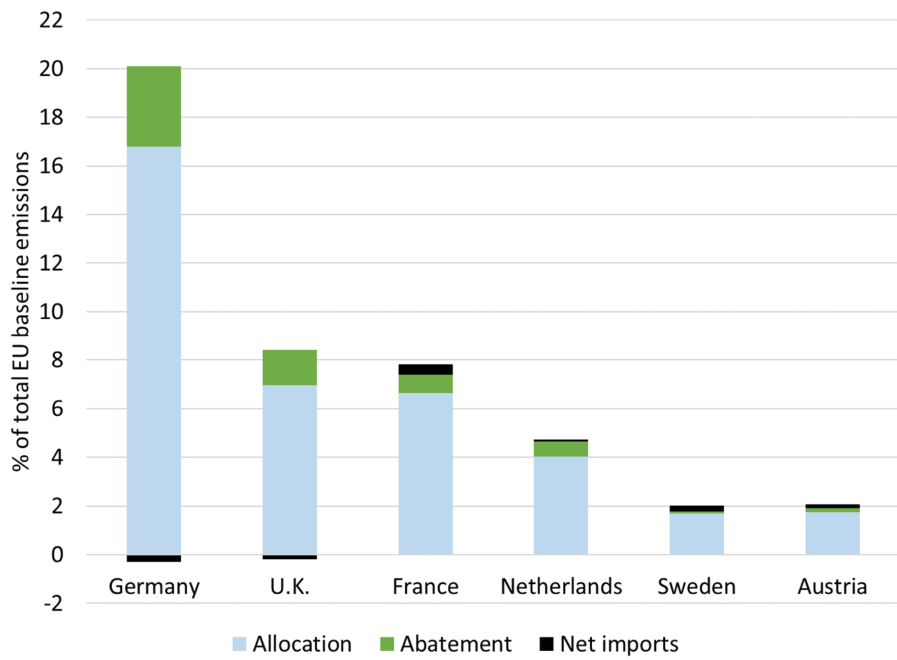
[13] Germany has 326 mt, U.K. 135 mt, France 129 mt, Netherlands 78 mt, Austria 34 mt, Sweden 33 mt, and Rest of EU has 911 mt.

[14] Since the ETS emissions reduction requirement of 15.2 percent is assumed to be spread uniformly across all member states, we can multiply each country's initial emissions allocation by 1/(1 – 0.152) to obtain its baseline emissions.

emissions), Germany and the United Kingdom are net exporters of emissions allowances and abate more than the average of 15.2 percent, whereas the countries with more expensive abatement options—France, the Netherlands, Austria, and Sweden—turn into net importers.

Figure 6 decomposes baseline emissions for each of the six jurisdictions into the allocation of emissions allowances, abatement, and net imports for the reference situation, scaled as a percentage of total EU baseline emissions. Together, the six jurisdictions represent approximately 45 percent of all emissions allocated in the EU ETS.

Figure 6. Allowance allocation, abatement, and net imports in 2018 (percentage of total EU baseline emissions)



Germany stands out for the largest allowance allocation and abatement effort, as well as being a net exporter of allowances. The United Kingdom has a similar but smaller profile. France is notable as an initial net importer of allowances, with less abatement activity than the similarly sized United Kingdom. The Netherlands is a slight net importer of allowances. Sweden, with the steepest MAC curve, relies the most on importing allowances, as a share of its compliance, followed by Austria; each accounts for less than 2 percent of the cap.

4. Simulation results

Recall that the unilaterally acting jurisdiction has three options to raise its domestic CO_2 price towards the targeted price floor: (1) imposing an additional domestic CO_2 tax (scenario *TAX*), (2) deleting emissions allowances (scenario *KILL*), and (3) requiring domestic firms to submit a multiple of emissions allowances for each ton of CO_2 emitted (scenario *BILL*). In our simulation analysis, we investigate how CO_2 price floors—ranging from the reference price level of €15 to a hypothetical upper bound of €100 per ton—affect the EU-wide ETS price, emissions abatement, economic welfare, and EU-wide cost-effectiveness.[15]

For brevity, we focus our discussion on Germany as the unilaterally acting jurisdiction. Germany stands out for having the highest CO_2 emissions and the largest allocation of emissions allowances. If not explicitly mentioned, the qualitative insights apply to other EU countries as well.

Section 4.1 begins with a discussion of how market fundamentals such as the ETS allowance price and emissions abatement respond to the different price floor options. Section 4.2 presents the welfare effects for our central case scenario, focusing only on the compliance costs. Section 4.3 reveals how the unilaterally acting jurisdiction would set its optimal CO_2 price floor under the three policy options when considering positive fiscal effects from additional public revenues, and Section 4.4 accounts for climate damages. In Section 4.5, we provide a

[15] The algebraic model summary and the data provided in Appendix B are sufficient to replicate all of our simulation results.

comprehensive summary of optimal unilateral price floor strategies by individual jurisdictions and also account for interacting fiscal and environmental benefits.

4.1. Effects on allowance prices and emissions abatement

Figure 7 quantifies Proposition 1, showing how the ETS allowance price changes as Germany increases its domestic price. *KILL* has the strongest upward effect by aligning one-to-one the ETS allowance price with the domestic price floor, *BILL* has less than a one-to-one upward effect, and *TAX* has the waterbed effect of driving down the ETS allowance price. Both the ETS price increase under *BILL* and the ETS price decrease under *TAX* depend on the scope of CO_2 abatement of the unilaterally acting jurisdiction. The more abatement this jurisdiction undertakes for a given increase in the domestic CO_2 price, the stronger is the downward pressure on the ETS allowance price for scenario *TAX*. The upward pressure on the ETS allowance price for scenario *BILL* is to a large extent driven by the jurisdiction's initial share of ETS emissions in the reference situation. The higher the share, the more its overcompliance will increase the effective EU-wide allowance demand and drive up the ETS allowance price. Thus, of our jurisdictions, Germany has the strongest influence on system-wide prices (see Figure 7). Note also that, ceteris paribus, the upward pressure from *BILL* will be weakened for jurisdictions with flatter MAC curves (i.e., the more elastic emissions abatement is to an increase in marginal abatement cost), since more domestic reductions mean less excess demand for allowances. For *TAX*, flatter MAC curves lead to a stronger downward pressure on the system-wide price. (From Figure 5, we see that Germany has a relatively flat MAC curve.)

Figure 7. ETS allowance price (€/tCO_2) with Germany as unilaterally acting jurisdiction

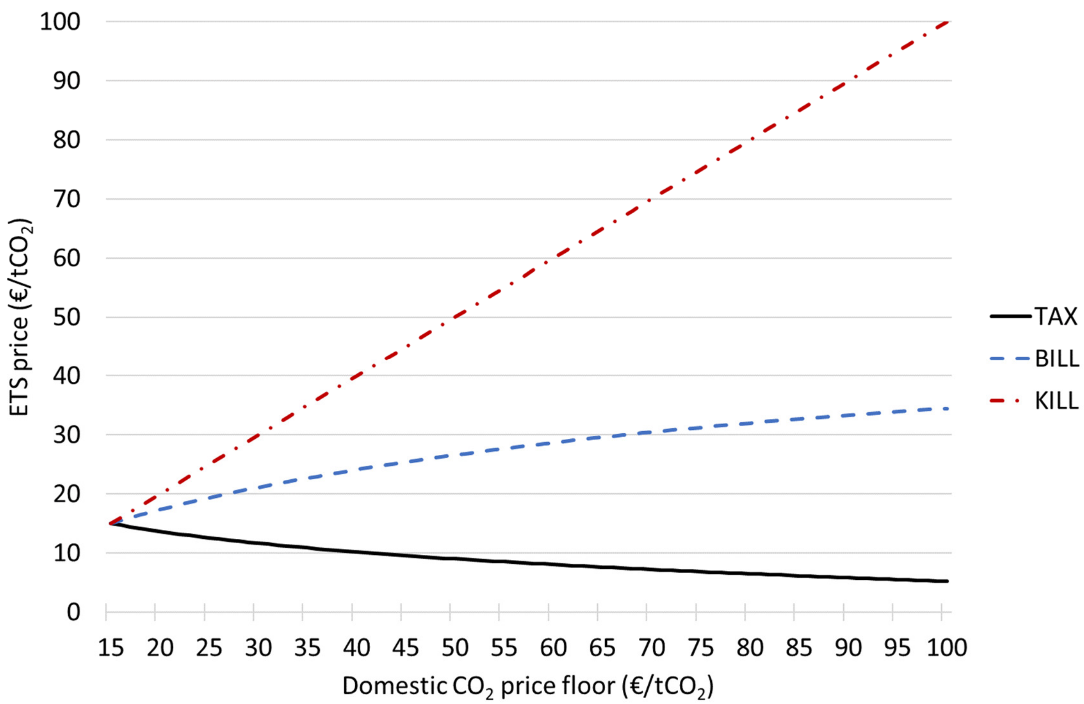


Figure 8. Abatement (mtCO₂) by Germany and EU with Germany as unilaterally acting jurisdiction

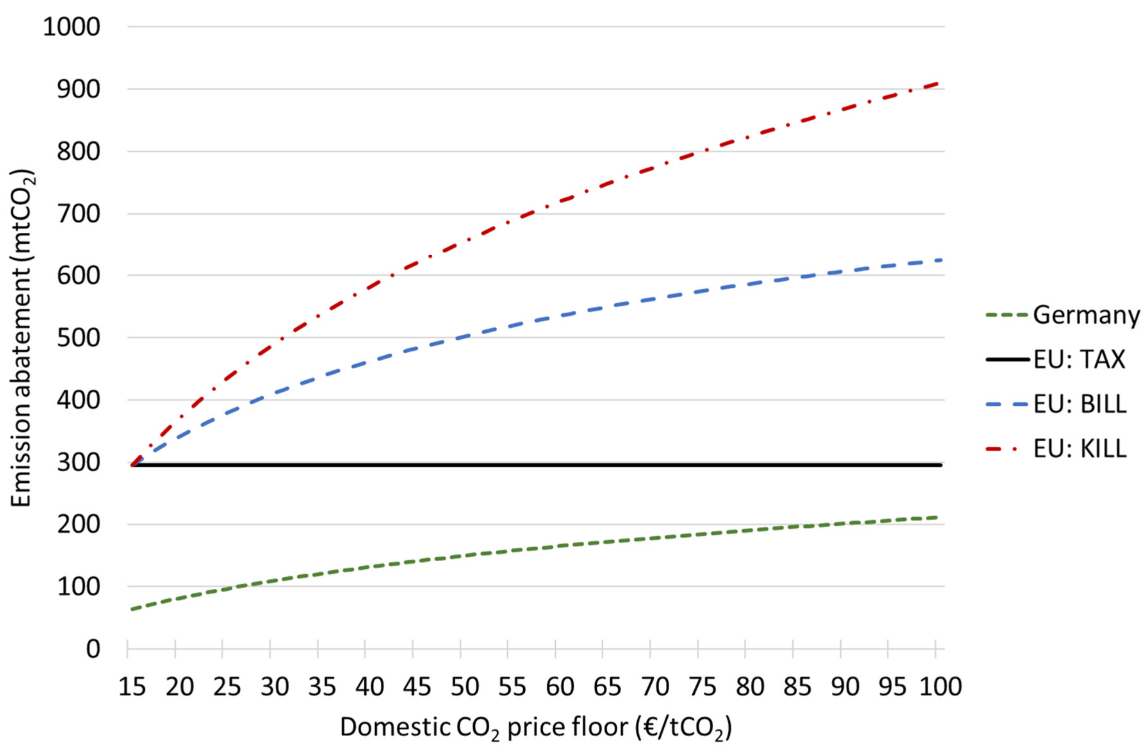


Figure 8 reports the emissions abatement in the ETS associated with different CO_2 pricing options. As the unilaterally acting jurisdiction, Germany undertakes the same amount of abatement regardless of the policy option for a given domestic price floor, and its abatement increases with the increase in the domestic CO_2 price floor. For the European Union as a whole, emissions abatement remains constant for scenario *TAX*, since it is determined by the ETS cap[16]; abatement in other member states is simply crowded out by increased abatement in Germany—the waterbed effect. For scenarios *BILL* and *KILL*, all other member states undertake more abatement in line with the increasing ETS allowance prices, leading to considerable additional abatement for scenario *BILL* and even more so for scenario *KILL.* Note that EU-wide abatement in scenario *KILL* emerges from identical (equalized) CO_2 prices across all member states and therefore will be the same for a given CO_2 price floor independent of the size of the unilaterally acting jurisdiction.

4.2. Compliance costs in the absence of fiscal or environmental benefits

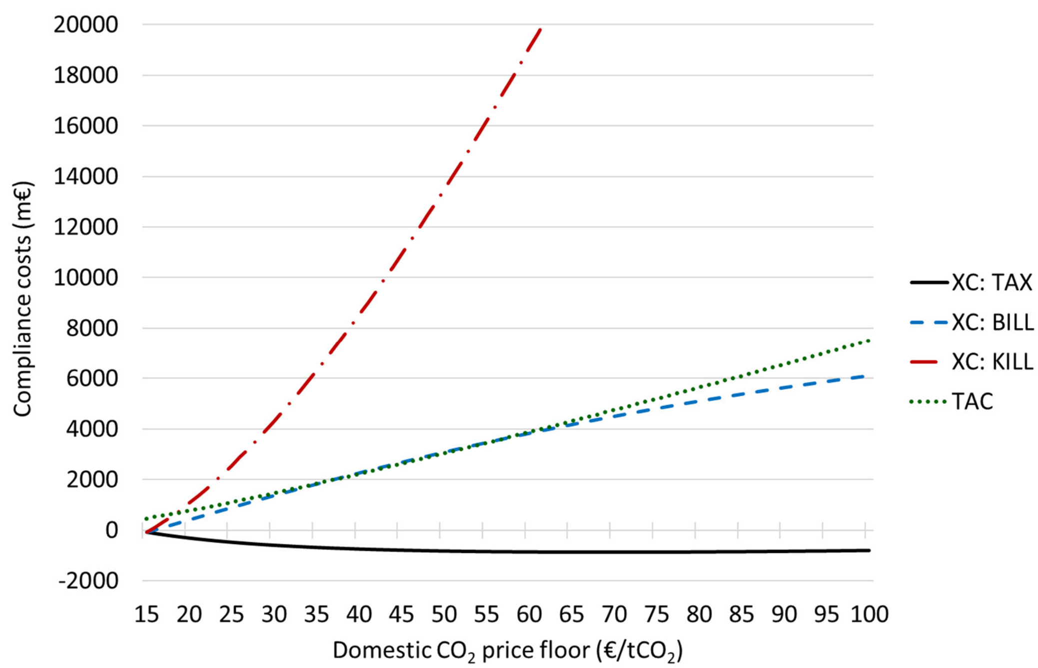
Figure 9 shows that the three price floor options have very different effects on the trade costs component of total compliance costs (labelled "XC") for the unilaterally acting jurisdiction, while they entail the same abatement costs (labelled "TAC"). Under *TAX*, Germany becomes a larger exporter of allowances, whereas under *BILL* and especially *KILL*, it increasingly needs to import allowances.

In the absence of fiscal and environmental benefits, the sole incentive to set a higher price floor is terms-of-trade gains that offset the increase in direct abatement costs. In theory, this could apply to an exporter of allowances in the case of *BILL* and *KILL*, or to an importer of

[16] This result holds as long as the ETS allowance price remains positive, which it does in the range of prices we consider for unilaterally acting jurisdictions.

allowances in the case of *TAX*. Based on our empirical data, no member state has an initial terms-of-trade incentive: each unilaterally acting jurisdiction will suffer from an increase in compliance costs as it moves towards higher domestic price floors. Figure 9 visualizes for the case of Germany how the increase in direct abatement costs ("TAC") is not offset through changes in trade costs ("XC") in the case of *TAX*, whereas for *BILL* and in particular *KILL,* the trade cost component adds substantially to overall compliance costs. In fact, trade costs under *KILL* exceed €45 billion at a CO_2 price of €100 per ton.

Figure 9. Abatement costs (*TAC*) and trade costs (*XC*) with Germany as unilaterally acting jurisdiction



The composite of other EU jurisdictions benefits from unilateral price floor policies. In scenario *TAX*, Rest of EU gains through the decline in the ETS allowance price, which reduces its effective abatement burden and expenditure per unit of imported allowance.[17] In scenarios

[17] If all other EU countries together were initially a larger exporter of allowances, they would suffer a loss in the terms of allowance trade. However, this is not the case in our empirical setting.

BILL and *KILL*, the higher ETS allowance prices trigger additional abatement efforts in Rest of EU; however, the increase in abatement costs is more than offset by the higher revenues from exporting allowances to the unilaterally acting country (see Figure 9, where net imports by the unilaterally acting jurisdiction equal the net exports of the other ETS members). The decrease in compliance cost for the others is especially pronounced in scenario *KILL*, where ETS allowance prices and export revenues are highest, leading to substantial value transfers from the unilaterally acting jurisdiction.

A related question regards the EU-wide costs of achieving a given amount of additional emissions abatement—that is, overall cost-effectiveness. When we abstain from unilateral valuations of fiscal benefits or climate damages, overall cost-effectiveness implies that marginal abatement costs across all jurisdictions are equalized. Whereas scenario *KILL* by definition aligns the domestic CO_2 price floor with the ETS market price, scenario *BILL* and in particular scenario *TAX* drive a wedge between the domestic price floor and the ETS allowance price (Figure 7), thereby inducing efficiency losses in EU-wide emissions abatement. The *TAX* policy entails higher EU-wide costs without any additional EU-wide abatement. Although the *BILL* policy does increase total abatement, it distorts the efficient allocation of those efforts among member states. Figure 10 shows the price divergence for a given amount of abatement.

Figure 11 provides insights into the compliance cost differences that result from these price differences. The x-axis indicates the additional EU-wide emissions abatement triggered by higher ETS prices in scenarios *BILL* and *KILL*. The y-axis reports the additional compliance costs, both for the European Union as a whole and for Germany as the unilaterally acting jurisdiction. We see that the EU-wide excess cost of *BILL* over *KILL* is negligible at moderate CO_2 price floor levels and remains moderate (around 20 percent as we move towards the upper

CO_2 price floor). In contrast to the cost ranking from an EU-wide perspective, Germany as the unilaterally acting jurisdiction has a preference for *BILL* because of its ability to leverage the emissions of its domestic firms to remove allowances and raise the EU ETS price. In contrast, countries with small emissions shares (e.g., Sweden) have very little leverage and hence prefer *KILL*. The increased cost burden from additional abatement is higher for the unilaterally acting jurisdiction than the EU-wide burden, echoing the findings of Figure 9 that the remaining member states tend to benefit from *BILL* and *KILL* policies (because the increase in their exported allowance values outweighs their additional compliance costs).

Figure 10. Emissions prices (€/tCO_2) in the unilaterally acting jurisdiction (Germany) and prevailing in EU market for given level of additional EU-wide abatement (mtCO_2)

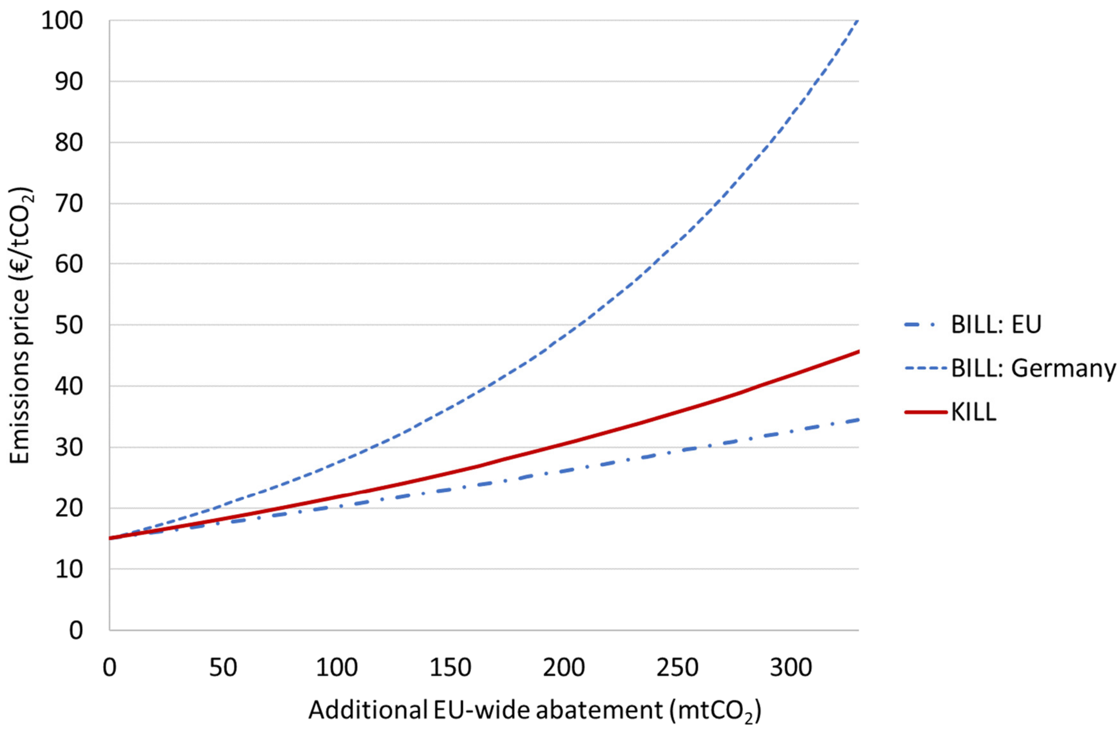
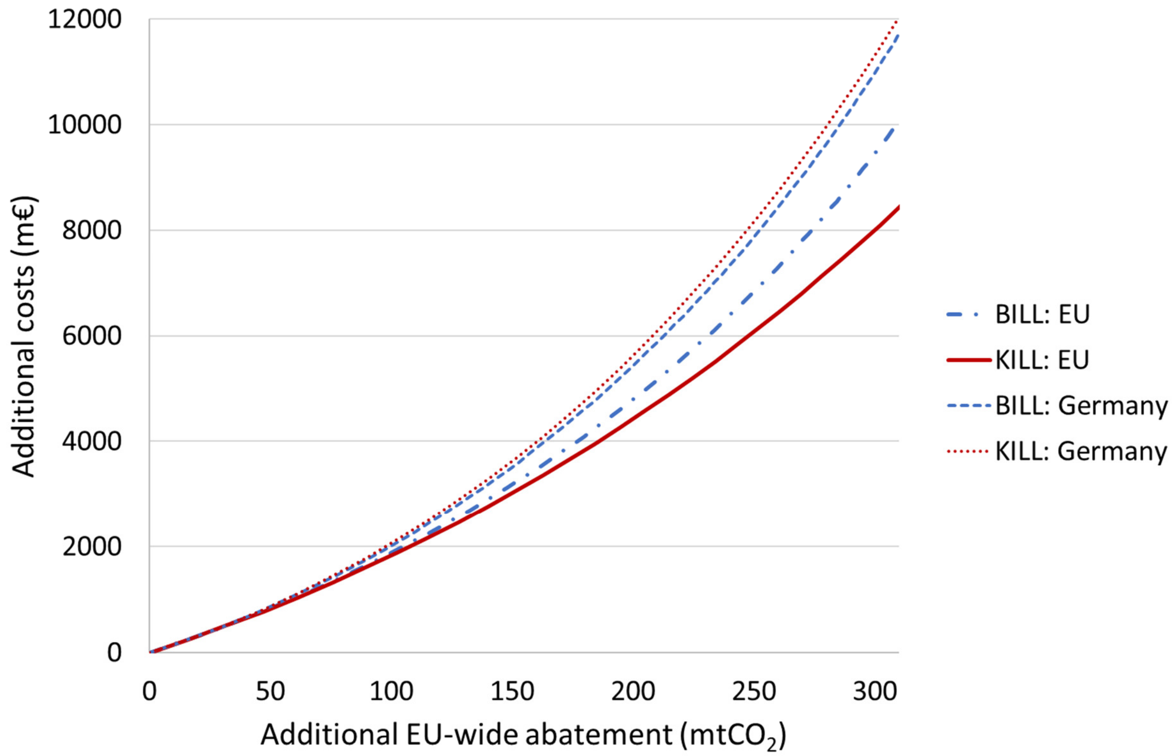


Figure 11. Cost implications of *BILL* versus *KILL* for given level of additional abatement with Germany as unilaterally acting jurisdiction



4.3. Fiscal benefits

So far, we have not considered any fiscal motive for setting domestic CO_2 price floors; we have assumed no extra value is placed on revenues for public coffers ($\gamma = 0$). However, additional tax revenues can provide additional economic benefits, for a variety of reasons. One might be that, from the viewpoint of political economy, voters tend to favor earmarking (Baranzini and Carattini 2017; Bristow et al. 2010; Kallbekken et al. 2011). For example, 80 to 90 percent of the carbon auction revenues in the EU ETS are dedicated to fund innovation and investments in low-carbon technologies (Le Den et al. 2017; Santikarn et al. 2019). To the extent these environmental expenditures address other market failures (like external knowledge spillovers from innovation), then raising revenues for them can have additional efficiency gains.

Another common public finance argument is that emissions revenues can allow reductions of other distortionary taxes and thereby decrease the excess burden of public taxation. Such revenue-recycling strategies are at the core of the double-dividend proposition that has figured prominently in the discussion of green tax reforms since the early 1990s (see, e.g., Goulder 1995 or Bovenberg 1998). Taxes are necessary to finance public expenditures, but they typically distort economic decisions as taxpayers try to avoid tax payments. The so-called marginal cost of public funds measures the welfare loss a society incurs in raising an additional unit of tax revenue. To the extent that CO_2 pricing has a lower marginal cost of public funds than preexisting taxes, additional CO_2 revenues carry an extra monetary value to the society. As an indication of the potential extra value of revenues from an environmental tax that is recycled against distortionary other taxes, Barrios et al. (2013) estimate the marginal cost of public funds associated with labor taxes ranges between 1.25 and more than 2 across EU member states.

In our theoretical analysis, we used γ as the extra weight on government revenues relative to the cost borne by domestic firms. For example, a value of 0.5 for γ would indicate a fiscal benefit of 50 cents per €1 of government revenue. In the previous section, we showed that compliance costs for the unilaterally acting jurisdiction increase as the domestic price floor rises from the reference price: additional costs were smallest for *TAX,* followed by *BILL* and *KILL.* When compliance costs are simply abatement and allowance trade costs, none of the price floor options provide cost savings for the unilaterally acting jurisdiction, compared with the reference situation. When we account for the revenue component, CO_2 price floor policies can become attractive to the extent that the increase in fiscal benefits more than offsets the additional cost for abatement and allowance trade. In the following scenarios, we assume that a member state's entire allowance allocation is auctioned, giving an upper bound to the fiscal benefits; to the extent that a significant share of those allowances is allocated to firms, those benefits will be attenuated.[18]

Figure 12. Government revenues (m€) with Germany as unilaterally acting jurisdiction

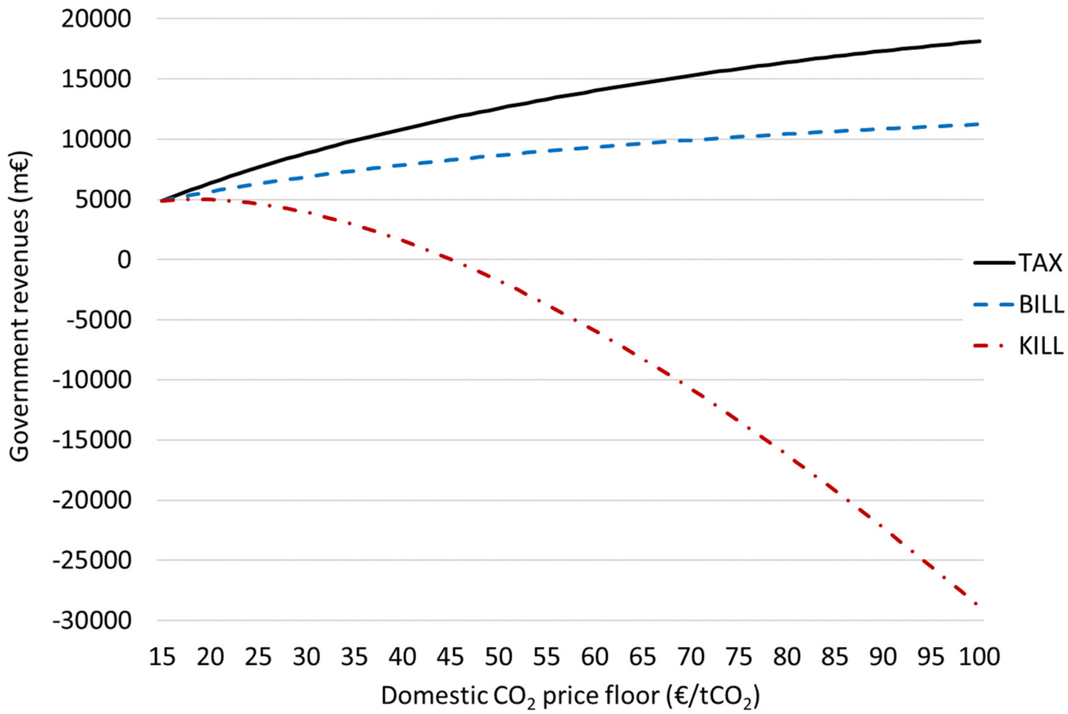


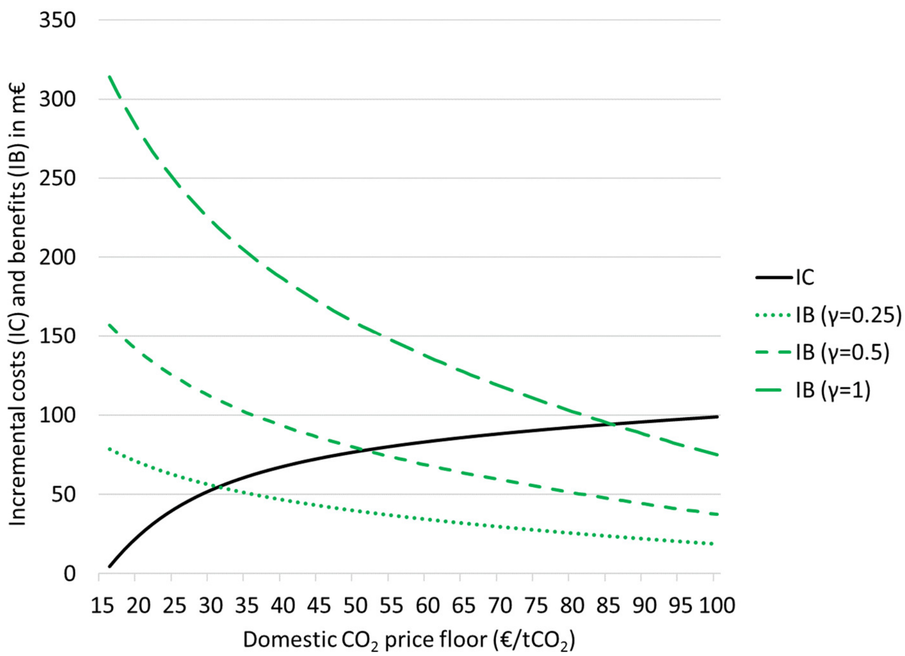
Figure 12 shows total revenues as a function of the domestic CO_2 price for the three policies. Following our theoretical exposition in Section 2, we see that *TAX* raises the most revenues, followed by *BILL*; *KILL* raises revenues initially but then induces a steep decline. In fact, at a reserve price of €45, Germany exhausts its allowance allocation and must use taxpayer funds to purchase and retire allowances.

Figure 13 depicts the trade-off between the incremental costs for emissions abatement and allowance trade on the one hand and the incremental fiscal benefits from government

[18] Over the course of Phase 3 of the EU ETS (2013–2020), manufacturing industry has received a gradually declining share of free allowances, reaching 30 percent in 2020. Power generators generally do not receive any free allowances. Over the entire period, 57 percent of the total amount of allowances were to be auctioned, with this share rising further in the next phase. https://ec.europa.eu/clima/policies/ets/auctioning_en

revenues on the other hand when Germany adopts *TAX* as its price floor strategy. Incremental costs and incremental benefits are computed for incremental price floor increases of €1. We indicate these trade-offs for increasing levels of γ (0.25, 0.5, and 1), which shift the incremental benefits curve upwards.

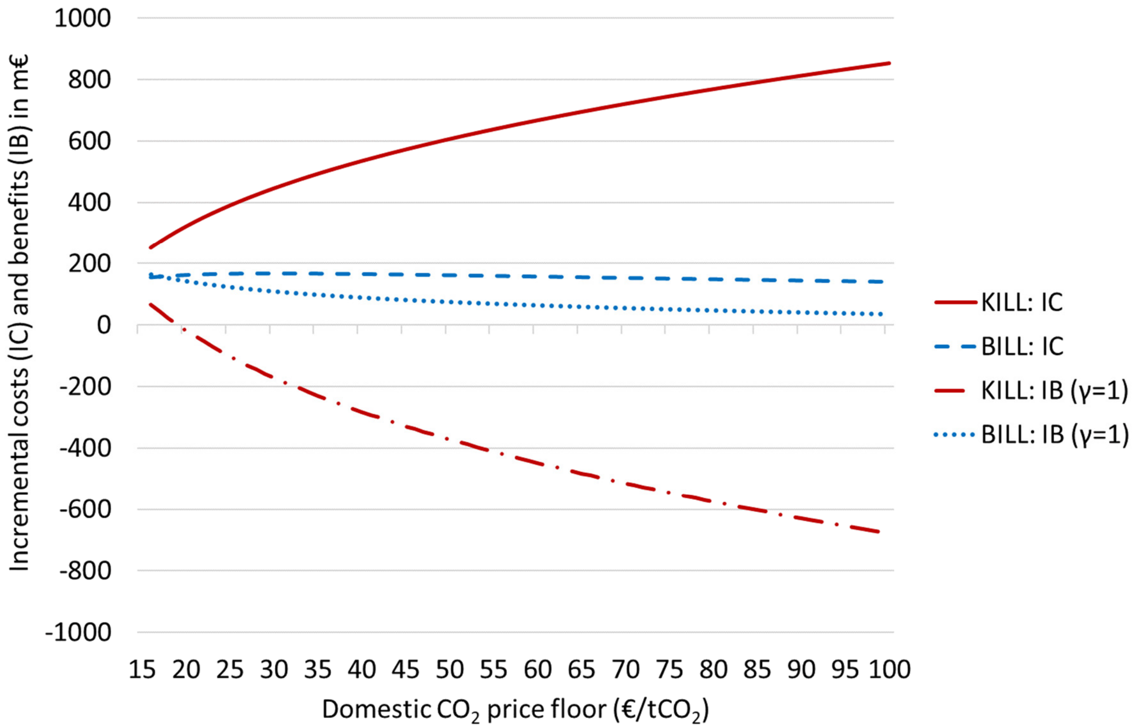
Figure 13. Incremental costs (IC) versus incremental benefits (IB) for fiscal benefits with Germany as unilaterally action jurisdiction, under *TAX*



The welfare-maximizing CO_2 price floor for Germany under scenario *TAX* increases from its €15 reference value to €31 $(\gamma = 0.25)$, via €51 $(\gamma = 0.5)$, up to €85 $(\gamma = 1)$, generating cost savings of 501 m€ $(\gamma = 0.25)$, 2005 m€ $(\gamma = 0.5)$, and 7112 m€ $(\gamma = 1)$, compared with the reference situation.

Figure 14 shows that incremental costs dominate incremental benefits for option *BILL* and even more so for *KILL*. The figure adopts our most optimistic assumption on the magnitude of fiscal benefits with $\gamma = 1$.

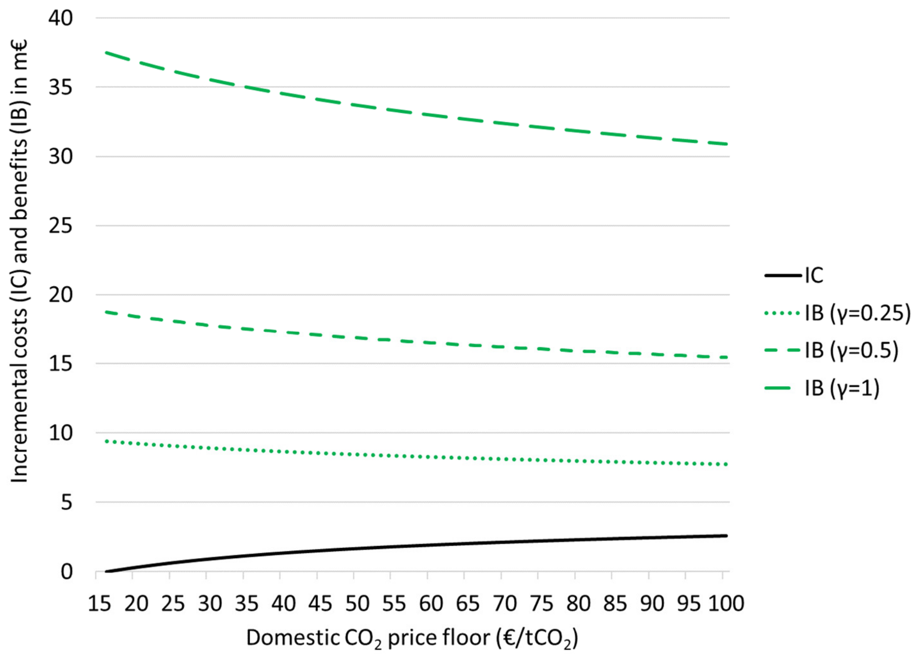
Figure 14. Incremental costs (IC) versus incremental benefits (IB) for fiscal benefits with Germany as unilaterally acting jurisdiction, under *BILL* and *KILL*



Only for *BILL* is there a narrow incentive for Germany to raise its price floor from the €15 reference level to €17 (and thereby achieve a rather small cost savings of €13 million). KILL never becomes attractive: the gap between higher incremental costs and lower incremental benefits widens more and more. The bad performance of KILL can be traced to the forgone auction revenues from withholding allowances to raise the domestic price floor.

For all other individual member states, neither *BILL* nor *KILL* pays off when fiscal benefits are accounted for. *TAX*, however, is a viable option, given its superior revenue-raising property and the limited increase in total compliance cost as the sum of direct abatement costs and net trade costs. The optimal *TAX* price floor is driven by the country-specific characteristics in marginal abatement cost curves. With a steeper MAC curve, an increase in the price floor induces a smaller decline in domestic emissions, meaning more revenues are raised; at the same time, less pressure on the ETS price means the change in trade costs is smaller. Countries with very steep MAC curves (e.g., Austria, Sweden) will pick their optimal *TAX* price floors at the upper limit of €100 with lower rates for fiscal benefits (see Section 4.5). Figure 15 illustrates this finding for Sweden.

Figure 15. Incremental costs (IC) versus incremental benefits (IB) for fiscal benefits with Sweden as unilaterally acting jurisdiction, under *TAX*



4.4. Environmental benefits

In our central case simulations (Section 4.2), we have not taken into account climate damages that might provide another rationale for unilateral CO_2 pricing strategies. If higher domestic price floors lead to a decline in EU-wide emissions, gross economic gains will be realized from reduced climate damages.

From a social planner's perspective, the value of abating a ton of CO_2 is referred to as the social cost of carbon (SCC), which is a monetary estimate of global climate change damages to society from an additional unit of carbon dioxide emissions. The SCC is used to value the benefits of CO_2 reductions from policies; in policy practice, governmental agencies may be legally required to value changes in CO_2 emissions in rulemakings (thereby assessing the potential benefits of CO_2 reductions from regulations). The explicit valuation of emissions reductions above the prevailing ETS price can provide incentives for a member state to undertake *BILL* and *KILL* pricing strategies; such incentives do not prevail for the case of a *TAX* strategy, which leaves EU-wide emissions unchanged, provided the ETS allowance price does not fall to zero.[19] We investigate the implications of emissions valuations for unilateral pricing strategies with *KILL* or *BILL* at alternative SCC levels of €25 and €50 per ton of CO_2.[20]

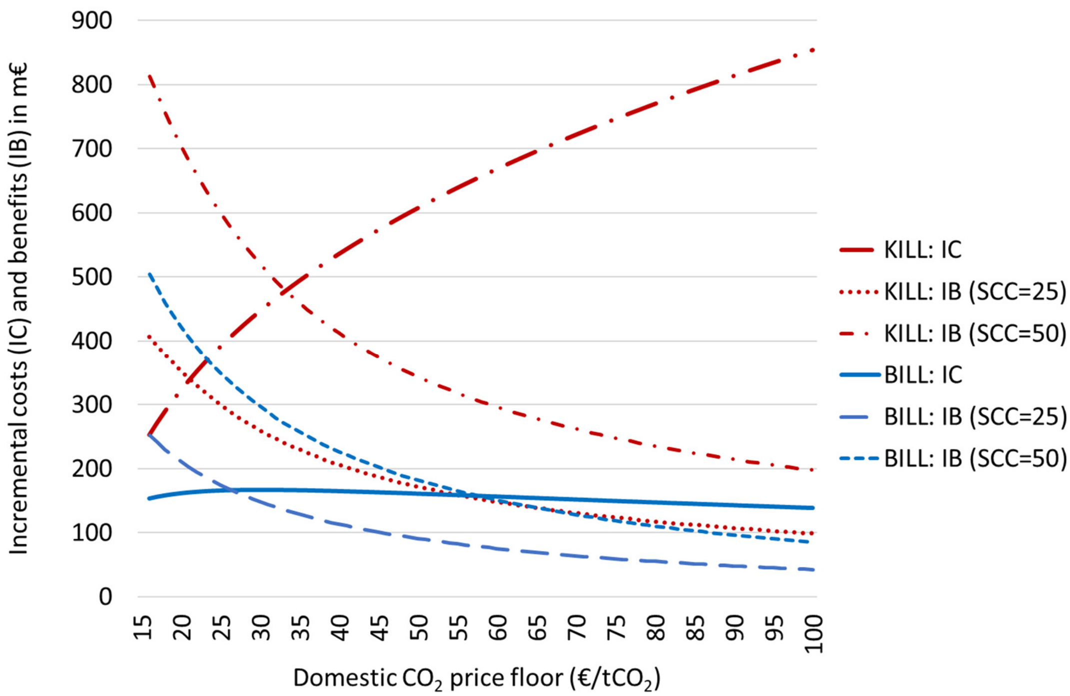
Figure 16 reports incremental benefits and incremental costs of unilateral pricing strategies for Germany over the domestic price floor range of €15 to €100 for *KILL* and *BILL*, as a function of the SCC. The incremental costs of emissions abatement and allowance trade are weighed against the value of additional allowance invalidation, which increases with the SCC. We observe that *KILL* is both more effective (with higher incremental benefits) and more costly (with higher incremental costs) than *BILL*. The optimal unilateral price floor is seen at the intersection of incremental costs and benefits for each scenario. The optimal *KILL* price floor is lower than the SCC because of the incremental trade costs. Meanwhile, the optimal *BILL* price floor is higher than the SCC because of the price wedge between domestic and systemwide prices, which remain below the SCC. With an SCC of €25/tCO_2, Germany chooses a domestic

[19] With an empirical parameterization of marginal abatement cost functions and the emissions reduction requirements of the reference situation, no member state is able to drive down the ETS price to zero towards the upper price bound of a €100/tCO_2.

[20] The wide range of SCC estimates can be traced to different cause-effect hypotheses in the natural science of climate change but also to ambiguous economic assumptions on the choice of discount rates, calculations of economic and noneconomic impacts, inequality aversion, etc. The US Interagency Working Group on Social Cost of Carbon (2016) provides estimates for 2020 that range from $12 to $62 for alternative discount rates, serving as a benchmark for our parametrization.

price of €21/tCO_2 for *KILL* and €26/tCO_2 for *BILL*; with an SCC of €50/tCO_2, the optimal price goes up to €33/tCO_2 for *KILL* and €57/tCO_2 for *BILL*.

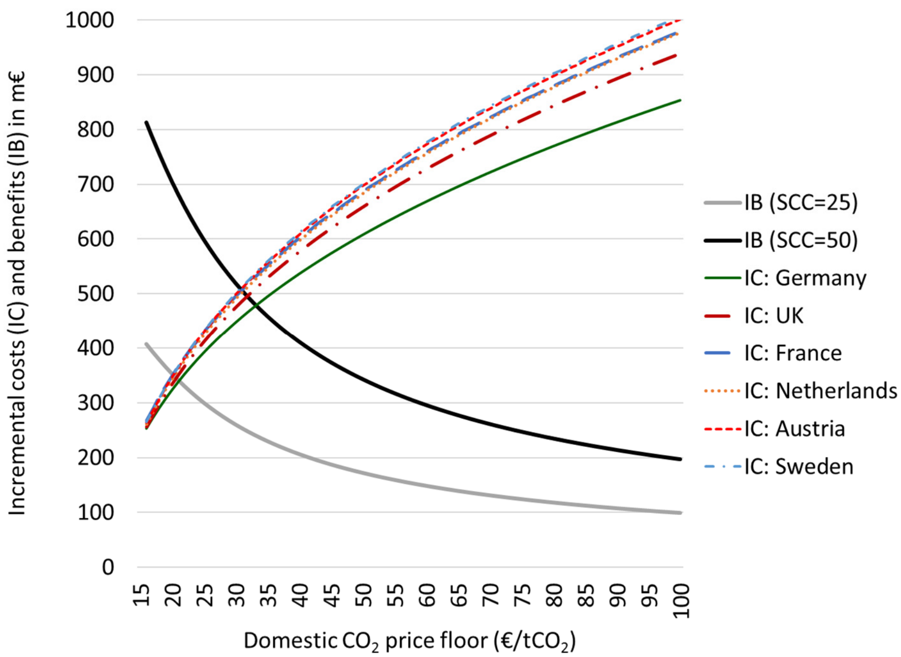
Figure 16. Incremental costs (IC) versus incremental benefits (IB) for environmental benefits with Germany as unilaterally acting jurisdiction



The welfare gains of optimal unilateral *KILL* and *BILL* strategies become substantial as we move towards higher valuation of climate damages. When Germany is the unilateral actor, its perceived *KILL* (*BILL*) gains amount to €455 million (€488 million) at an SCC of €25 per ton of CO_2, which increase to €4429 million (€4623 million) at an SCC of €50. Not surprisingly, the *KILL* and *BILL* welfare gains are very similar, since the marginal benefits of EU-wide emissions reduction are identical and the marginal costs of achieving EU-wide emissions reduction (as the direct costs for higher domestic abatement plus the indirect costs of compensating other member states for additional foreign abatement via invalidation or overcompliance) are quite similar across the policies (recall Figure 11).

Whereas *KILL* withdraws allowances from circulation directly, *BILL* does this through overcompliance, which is more effective the larger the country's share of emissions.[21] Larger countries with more room to reduce emissions below their allocations also experience lower trade costs from *KILL*, since the acting jurisdiction is responsible for invalidating the system-wide emissions reductions. Figure 17 illustrates this effect: the incremental benefits of *KILL* are identical across countries, but the incremental costs are declining with size. Smaller countries then prefer somewhat lower price floors.

Figure 17. Incremental costs (IC) versus incremental benefits (IB) for environmental benefits with unilaterally acting jurisdiction adopting *KILL*

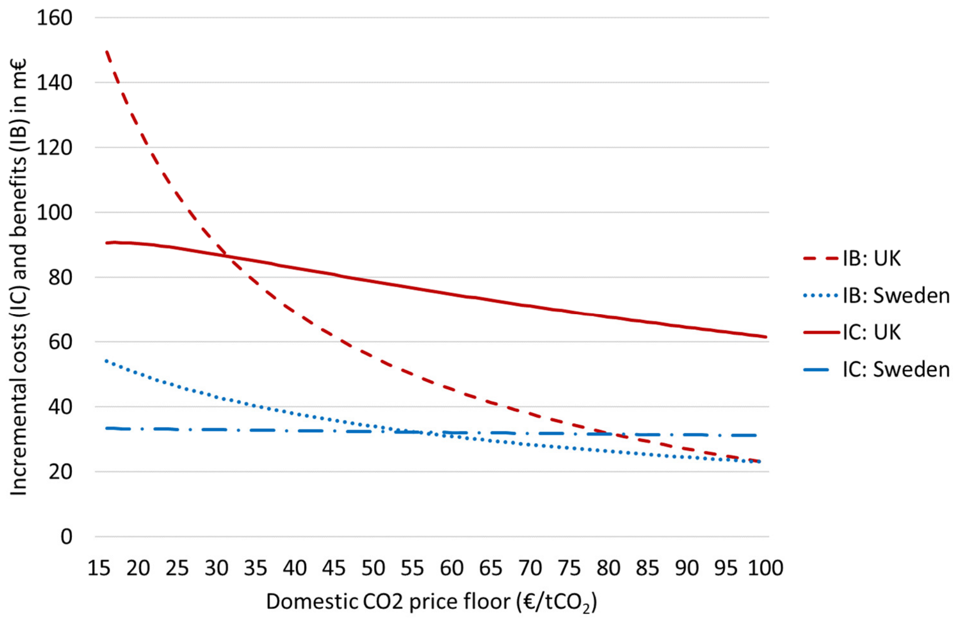


Meanwhile, the flatter is a country's marginal abatement cost curve, the more domestic reductions are realized, which improves environmental benefits. Both country size and flatter MAC curves drive the unilaterally optimal price floor closer to the SCC and close the gap

[21] Note that in a cooperative setting across all EU member states, the optimal price floor coincides with the ETS price at the level of the SCC, equalizing the EU-wide marginal abatement costs with the marginal benefits of emissions reduction. In the case of EU-wide cooperative action, the three floor price options become identical.

between *KILL* and *BILL* in the preferred price floors. Figure 18 illustrates this effect for the *BILL* strategy, contrasting Sweden (a small country with the steepest MAC curve) and the United Kingdom (a larger country with the flattest MAC curve) when the SCC value is €25. The United Kingdom has higher incremental costs but even higher incremental benefits, so it chooses a price floor of €31. By contrast, Sweden has low incremental benefits, having few domestic emissions to leverage with overcompliance, but even lower incremental costs, since its abatement is insensitive to the price; it then chooses a price floor of €55 to obtain more emissions reductions.

Figure 18. Incremental costs (IC) versus incremental benefits (IB) for environmental benefits (SCC=25) with Sweden or United Kingdom (UK) as unilaterally acting jurisdiction adopting *BILL*



4.5. Cross-comparison of optimal unilateral price floor strategies

Next, we summarize simulation results across all six EU countries considering domestic price floor policies: Germany, United Kingdom, France, Netherlands, Sweden, and Austria. We require that any price floor not fall below the EU ETS reference price of €15/tCO_2 or exceed an upper bound of €100/tCO_2. As seen in previous subsections, in its optimal unilateral pricing strategy, the individual country trades off the additional abatement and trade costs against its valuation of the fiscal and environmental benefits.

Table 1 presents the optimal (i.e., compliance cost–minimizing) unilateral policy, by country, for each policy option (*TAX, KILL,* and *BILL*) at different values of climate damages (SCC = 0, 25, 50) and fiscal benefits (γ = 0, 0.25, 0.5, 1). We report the optimal domestic price floor and the gains (cost savings) compared with the reference situation (in m€ and as a percentage). For each parameter combination of fiscal benefits and climate damages, we highlight the preferred instrument and indicate how the preferred price floor depends on the relative valuation of fiscal benefits and climate damages. Our insights can be summarized as follows.

First, with neither fiscal benefits (γ = 0) nor climate benefits (SCC = 0), all countries stick to the reference situation; there is no scope for exploiting terms of trade.

Second, when only fiscal benefits matter (SCC = 0; γ > 0), no member state has a strategic incentive to use *BILL* or *KILL* policies; *TAX* clearly dominates, being the best at raising revenue.[22] Differences in the optimal *TAX* price floor can be traced to the cross-country differences in MAC curves (and the initial size of emissions): small, abatement-inelastic countries like Austria or Sweden pick the upper limit of the domestic price floor, since compliance costs are low relative to the fiscal benefits. The net economic gains from increased domestic price floors in scenario *TAX* can be substantial relative to the reference situation as we account for fiscal benefits. For example, France's initial compliance costs of €231 million convert into positive welfare gains of €1167 million when $\gamma = 0.25$. As France increases the

[22] In fact, *KILL* never provides any welfare gains (cost savings), and *BILL* yields only a small gain for the country with the largest share of emissions (Germany) at a high valuation of fiscal benefits.

domestic price floor to the optimal level of €96 (with a domestic CO_2 tax of €83 per ton of CO_2) welfare gains are €916 million, or around 365 percent of the reference value when $\gamma = 0.25$.

Third, when only climate benefits matter (SCC > 0; γ =0), both *KILL* and *BILL* strategies are worth adopting unilaterally; *TAX* yields no environmental benefits. The cost savings potential of *KILL* and *BILL* are fairly similar—across both instruments and jurisdictions—reflecting the facts that marginal benefits of emissions reduction are identical for each unilaterally acting jurisdiction and that the marginal costs of EU-wide emissions reduction are determined by the abatement characteristics across all EU member states, rather than the abatement options of the individual country. The main differences arise from variation in trade costs (for *KILL*) and ability to raise ETS allowance prices (for *BILL*). The welfare gains themselves are rather modest: relative to the economic situation at the initial ETS price of €15, the benefits are around 1 percent at an SCC of €25 and between 3.3 and 5.7 percent at an SCC of €50. With *KILL*—where the domestic price floor is identical to the ETS price—countries choose values that are lower than the SCC, reflecting the burden of acting unilaterally, but those values are roughly the same across countries (as reflected in Figure 17). By contrast, with *BILL*, domestic price floors are higher than the SCC and show larger variations across countries, largely because of differences in emissions shares. Smaller countries exert less influence on emissions with overcompliance and therefore pick higher optimal domestic price floors than larger countries; however, the corresponding ETS prices remain lower than the SCC and rather similar to those that would have been chosen under *KILL* strategies.

Fourth, when both fiscal and environmental benefits are present (SCC > 0; γ =0), policy choices shift depending on the relative importance of those benefits. When fiscal benefits are relatively more important, *TAX* dominates. However, when the SCC is important as well, *BILL* is preferred. Having the lowest revenues, *KILL* is too costly when $\gamma > 0$. *BILL* can deliver both emissions reductions and increased revenues. For both *TAX* and *BILL*, the smaller a country's initial emissions share, the higher is the domestic price floor needed to obtain a given fiscal benefit for a given increase in the ETS price for the same environmental benefits. Therefore, we see small countries choose higher prices than large countries and even approach the upper-bound price floor of €100 when fiscal benefits are high or the SCC approaches €50.

Table 2. Optimal price floor policies by unilaterally acting jurisdiction

		TAX			***BILL***			***KILL***		
SCC (€/tCO_2)	γ	Price (€/tCO_2)	Gains (m€, %)		Price (€/tCO_2)	Gains (m€, %)		Price (€/tCO_2)	Gains (m€, %)	
Germany										
0	0	15	0	0.0	15	0	0.0	15	0	0.0
0	0.25	31	501	59.8	15	0	0.0	15	0	0.0
0	0.5	51	2005	97.3	15	0	0.0	15	0	0.0
0	1	85	7112	157.9	17	13	0.3	15	0	0.0
25	0	15	0	0.0	26	488	1.2	21	455	1.1
25	0.25	31	501	1.2	31	946	2.3	20	480	1.2
25	0.5	51	2005	5.1	37	1556	4.0	20	508	1.3
25	1	85	7112	19.4	51	3213	8.8	20	564	1.5
50	0	15	0	0.0	57	4673	5.7	33	4429	5.4
50	0.25	31	501	0.6	64	5796	7.1	31	4110	5.0
50	0.5	51	2005	2.5	71	7023	8.8	29	3879	4.8
50	1	85	7112	9.1	85	9752	12.5	27	3566	4.6
United Kingdom										
0	0	15	0	0.0	15	0	0.0	15	0	0.0
0	0.25	34	263	72.8	15	0	0.0	15	0	0.0
0	0.5	55	976	112.3	15	0	0.0	15	0	0.0
0	1	84	3155	167.5	15	0	0.0	15	0	0.0
25	0	15	0	0.0	31	393	1.0	20	415	1.0
25	0.25	34	263	0.6	34	530	1.3	19	238	0.6
25	0.5	55	976	2.4	37	684	1.7	17	129	0.3
25	1	84	3155	8.0	44	1046	2.7	16	26	0.1
50	0	15	0	0.0	75	3581	4.3	31	4123	5.0
50	0.25	34	263	0.3	78	3891	4.7	28	3208	3.9
50	0.5	55	976	1.2	80	4208	5.2	26	2534	3.1
50	1	84	3155	3.9	86	4861	6.0	22	1623	2.0
France										
0	0	15	0	0.0	15	0	0.0	15	0	0.0

0	0.25	96	916	364.5	15	0	0.0	15	0	0.0
0	0.5	100	3065	417.7	15	0	0.0	15	0	0.0
0	1	100	7366	433.6	15	0	0.0	15	0	0.0
25	0	15	0	0.0	30	351	0.8	20	348	0.8
25	0.25	96	916	2.2	33	497	1.2	18	193	0.5
25	0.5	100	3065	7.6	37	669	1.7	17	98	0.2
25	1	100	7366	18.7	46	1097	2.8	16	7	0.0
50	0	15	0	0.0	78	3775	4.6	31	3856	4.7
50	0.25	96	916	1.1	84	4204	5.1	27	2986	3.6
50	0.5	100	3065	3.8	90	4659	5.7	25	2346	2.9
50	1	100	7366	9.1	100	5648	7.0	22	1478	1.8

Table 1, cont. Optimal price floor policies by unilaterally acting jurisdiction

		TAX			***BILL***			***KILL***		
SCC (€/tCO_2)	γ	CO_2 Price (€/tCO_2)	Gains (m€, %)		Price (€/tCO_2)	Gains (m€, %)		Price (€/tCO_2)	Gains (m€, %)	
					Netherlands					
0	0	15	0	0.0	15	0	0.0	15	0	0.0
0	0.25	49	265	147.7	15	0	0.0	15	0	0.0
0	0.5	87	1008	213.4	15	0	0.0	15	0	0.0
0	1	100	3057	289.1	15	0	0.0	15	0	0.0
25	0	15	0	0.0	36	338	0.8	20	379	0.9
25	0.25	49	265	0.6	39	411	1.0	18	174	0.4
25	0.5	87	1008	2.5	41	490	1.2	17	60	0.1
25	1	100	3057	7.6	47	668	1.7	15	0	0.0
50	0	15	0	0.0	99	3223	3.9	31	3947	4.8
50	0.25	49	265	0.3	100	3402	4.1	27	2905	3.5
50	0.5	87	1008	1.2	100	3582	4.4	25	2153	2.6
50	1	100	3057	3.8	100	3940	4.9	21	1186	1.5
					Sweden					
0	0	15	0	0.0	15	0	0.0	15	0	0.0
0	0.25	100	566	1222.5	15	0	0.0	15	0	0.0
0	0.5	100	1277	749.7	15	0	0.0	15	0	0.0
0	1	100	2699	645.1	15	0	0.0	15	0	0.0
25	0	15	0	0.0	55	333	0.8	20	358	0.9
25	0.25	100	566	1.4	58	369	0.9	18	129	0.3
25	0.5	100	1277	3.1	60	406	1.0	16	28	0.1
25	1	100	2699	6.6	66	485	1.2	15	0	0.0
50	0	15	0	0.0	100	2981	3.6	30	3838	4.7
50	0.25	100	566	0.7	100	3044	3.7	26	2697	3.3
50	0.5	100	1277	1.6	100	3108	3.8	24	1901	2.3
50	1	100	2699	3.3	100	3234	3.9	20	902	1.1
					Austria					

0	0	15	0	0.0	15	0	0.0	15	0	0.0
0	0.25	100	346	595.4	15	0	0.0	15	0	0.0
0	0.5	100	969	522.6	15	0	0.0	15		0.0
0	1	100	2215	503.4	15	0	0.0	15	0	0.0
25	0	15	0	0.0	53	311	0.8	20	365	0.9
25	0.25	100	346	0.8	56	343	0.8	18	134	0.3
25	0.5	100	969	2.4	58	376	0.9	16	30	0.1
25	1	100	2215	5.4	63	448	1.1	15	0	0.0
50	0	15	0	0.0	100	2748	3.3	30	3865	4.7
50	0.25	100	346	0.4	100	2805	3.4	27	2719	3.3
50	0.5	100	969	1.2	100	2862	3.5	24	1919	2.3
50	1	100	2215	2.7	100	2976	3.6	20	914	1.1

5. Concluding remarks

The desire to increase domestic CO_2 prices through unilateral action, even though a jurisdiction already participates in multilateral emissions trading, is not confined to the European Union. New York State's Independent System Operator has proposed a carbon pricing adder to electricity dispatch prices, despite its participation in the Northeastern Regional Greenhouse Gas Initiative.[23] In this paper, we have investigated three options for setting minimum CO_2 prices unilaterally: (1) a *TAX* policy, where the domestic government levies an additional CO_2 tax on top of the broader trading system's prevailing emissions allowance price; (2) a *KILL* policy, where invalidation of emissions allowances aligns the prevailing price with the targeted domestic minimum price; and (3) a *BILL* policy, where domestic overcompliance increases demand for allowances, which pushes up both the prevailing and the domestic CO_2 prices.

In theory, the optimal domestic price floor under each policy is influenced by some mix of three potential benefits: (1) the fiscal benefits of additional revenues, such as when public goods are financed by other distorting taxes, or if a dedicated revenue stream is required to fund

[23] https://www.forbes.com/sites/peterdetwiler/2020/02/20/in-a-path-breaking-approach-new-yorks-grid-operator-proposes-inclusion-of-carbon-costs-in-market-prices/ (accessed April 4, 2020).

underprovided goods; (2) the environmental benefits of additional (or displaced) emissions reductions, such as when the social cost of carbon exceeds the prevailing allowance price, or ancillary pollutants are unpriced; and (3) changes in the terms of allowance trade. *TAX* is the most effective for fiscal purposes but is impotent for reducing emissions because of the waterbed effect. *KILL* is the most efficient for reducing emissions but the costliest in terms of allowance trade and forgone fiscal benefits. Despite the higher domestic prices entailed, *BILL* is often the least costly strategy for the unilaterally acting jurisdiction to achieve environmental benefits, particularly if public revenues also have extra value.

For unilateral policies, the choice is generally between *TAX*, if the fiscal benefits are large and environmental benefits small, and *KILL,* if the environmental benefits are large and fiscal benefits negligible; *BILL* is suitable for many circumstances in between. These results may help explain why individual jurisdictions gravitate towards policies that impose excess cost on their domestic emitters, rather than simply contributing to the public good by unilaterally invalidating allowances.

Our analysis has several potential extensions. First, the theoretical model indicates that differentiated benefits from emissions abatement could be a driving factor; it would be interesting to include ancillary benefits from conventional pollutants, which vary substantially by member state, into our numerical model of unilateral price floor policies. Second, recent reforms to the EU ETS, in particular the market stability reserve and the possibility that excess allowances will be invalidated, introduce important complications that would be interesting to investigate (see Perino 2018). For one, the waterbed effect of *TAX* policies may be punctured; for another, emissions reductions (or unilaterally retired allowances) from *BILL* or *KILL* may enable some future allowances that would otherwise be cancelled to remain in the system. To analyse this issue, a dynamic model would be needed. Third, an important motivation for minimum prices is creating incentives for investment and technological innovation. To the extent that such innovation creates spillovers in terms of the marginal abatement cost and policy incentives of other member states, the EU-wide and domestic benefits of unilateral action can be quite different and influence current strategies. Lastly, in practice, several member states are considering raising their floor prices contemporaneously, though not in a coordinated fashion; this prospect raises interesting potential questions regarding strategic competition among heterogeneous jurisdictions and gains from cooperation. We plan to address these topics in future research.

References

Aguiar, Angel, Maxysm Chepeliev, Erwin L. Corong, Robert McDougall, and Dominique van der Mensbrugghe. 2019. The GTAP Data Base: Version 10. *Journal of Global Economic Analysis* 4 (1): 1–27.

Baranzini, Andrea, and Stefano Carattini. 2017. Effectiveness, Earmarking and Labeling: Testing the Acceptability of Carbon Taxes with Survey Data. *Environmental Economics and Policy Studies* 19 (1): 197–227.

Barrios, Salvado, Jonathan Pycroft, and Bert Saveyn. 2013. The Marginal Cost of Public Funds in the EU: The Case of Labour versus Green Taxes. Taxation Papers Working Paper 32. Brussels: European Commission.

Bovenberg, A. Lans. 1999. Green Tax Reforms and the Double Dividend: An Updated Reader's Guide. *International Tax and Public Finance* 6: 421–424.

Böhringer, Christoph, and Knut Einar Rosendahl. 2010. Green Promotes the Dirtiest: On the Interaction between Black and Green Quotas in Energy Markets. *Journal of Regulatory Economics* 37 (3): 316–25.

Böhringer, Christoph, Henrike Koschel, and Ulf Moslener. 2008. Efficiency Losses from Overlapping Regulation of EU Carbon Emissions. *Journal of Regulatory Economics* 33 (3): 299–317.

Böhringer, Christoph, Bouwe Dijkstra, and Knut Einar Rosendahl. 2014. Sectoral and Regional Expansion of Emissions Trading. *Resource and Energy Economics* 37: 201–25.

Böhringer, Christoph, Andy Müller, and Jan Schneider. 2015. Carbon Tariffs Revisited. *Journal of the Association of Environmental and Resource Economists* 2 (4): 629–72.

Bristow, Abigail L., Mark Wardman, Alberto M. Zanni, and Phani K. Chintakayala. 2010. Public Acceptability of Personal Carbon Trading and Carbon Tax. *Ecological Economics* 69 (9): 1824–37.

Brooke, Anthony, David Kendrick, and Alex Meeraus. 1987. *GAMS: A User's Guide.* South San Francisco: Scientific Press.

Dirkse, Steve, and Michael Ferris. 1995. The PATH Solver: A Non-monotone Stabilization Scheme for Mixed Complementarity Problems. *Optimization Methods and Software* 5: 123–56.

Edenhofer, Ottmar, Christian Flachsland, Christoph Wolff, Lisa Katharina Schmid, Anna Leipprand, Nicolas Koch, Ulrike Kornek, and Michael Pahle. 2017. Decarbonization and EU ETS Reform: Introducing a Price Floor to Drive Low-Carbon Investments. Policy Paper. Berlin: Mercator Research Institute on Global Commons and Climate Change.

Ellerman, A. Denny, Claudio Marcantonini, and Aleksandar Zaklan. 2016. The European Union Emissions Trading System: Ten Years and Counting. *Review of Environmental Economics and Policy* 10: 89–107.

European Commission (EC). 2009. Draft Commission Staff Working Document Impact Assessment Accompanying document to the Commission Decision determining a list of sectors and subsectors which are deemed to be exposed to a significant risk of carbon leakage pursuant to Article 10a (13) of Directive 2003/87/EC. Brussels, 24.12.2009, SEC(2009)10251 final.

European Union (EU). 2012. Consolidated Version of the Treaty on the Functioning of the European Union. Official Journal of the European Union. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:12012E/TXT&from=EN

———. 2018. Communication from the Commission. Publication of the Total Number of Allowances in Circulation in 2017 for the Purposes of the Market Stability Reserve under the EU.

Fischer, Carolyn, and Louis Preonas. 2010. Combining Policies for Renewable Energy: Is the Whole Less than the Sum of Its Parts? *International Review of Energy and Resource Economics* 4 (1): 51–92. doi:10.1561/101.00000030

Fischer, Carolyn, Leonie Reins, Dallas Burtraw, David Langlet, Asa Lofgren, Michael Mehling, Stefan Weishaar, Lars Zetterberg, Harro van Asselt, and Kati Kulovesi. 2020. The Legal and Economic Case for an Auction Reserve Price in the EU Emissions Trading System. 26 *Columbia Journal of European Law* 1 (Spring).

Flachsland, C., M. Pahle, D. Burtraw, O. Edenhofer, M. Elkerbout, C. Fischer, O. Tietjen & L. Zetterberg. 2020. How to avoid history repeating itself: the case for an EU Emissions

Trading System (EU ETS) price floor revisited, *Climate Policy*, 20:1, 133-142. doi: 10.1080/14693062.2019.1682494

Goulder, Larry H. 1995. Environmental Taxation and the Double Dividend: A Reader's Guide. *International. Tax and Public Finance* 2: 157–84.

Kallbekken, Steffen, Stephan Kroll, and Todd L. Cherry. 2011. Do You Not Like Pigou, or Do You Not Understand Him? Tax Aversion and Revenue Recycling in the Lab. *Journal of Environmental Economics and Management* 62 (1): 53–64.

Karp, Larry and Christian Traeger. 2017. Smart Cap. Manuscript. UC—Berkeley.

Le Den, Xavier, Edmund Beavor, Samy Porteron, and Adriana Ilisescu. 2017. Analysis of the Use of Auction Revenues by the Member States: Final Report. https://ec.europa.eu/clima/sites/clima/files/ets/auctioning/docs/auction_revenues_report_2017_en.pdf.

Perino, Grischa, and Maximilian Willner. 2016. Procrastinating Reform: The Impact of the Market Stability Reserve on the EU ETS. *Journal of Environmental Economics and Management* 80: 37–52.

Perino, Grischa. 2018. New EU ETS Phase 4 Rules Temporarily Puncture Waterbed. *Nature Climate Change* 8 (4): 262–64.

Ricke, Katharine, Laurent Drouet, Ken Caldeira and Massimo Tavoni. 2018. Country-level Social Cost of Carbon. *Nature Climate Change* 8: 895–900.

Rosendahl, Knut Einar. 2019. EU ETS and the New Green Paradox. Working Paper 2/2019. Norwegian University of Life Sciences School of Economics and Business.

Rutherford, Thomas Fox. 1995. Extensions of GAMS for Complementarity Problems Arising in Applied Economics. *Journal of Economic Dynamics and Control* 19: 1299–324.

Santikarn, Marissa, Christopher Kardish, Johannes Ackva, and Constanze Haug—ICAP Secretariat. 2019. The Use of Auction Revenue from Emissions Trading Systems: Delivering Environmental, Economic, and Social Benefits. Berlin: International Climate Action Partnership.

Interagency Working Group on Social Cost of Greenhouse Gases. 2016. Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866. August. Washington, DC: United States Government.

Appendix A. Derivations of analytical results

In each case, the unilateral jurisdiction maximizes welfare with respect to the domestic price. From (1),

$$\frac{\partial \Delta W_G}{\partial p_G} = \frac{\partial B_G}{\partial p_G} + \gamma \frac{\partial GR_G}{\partial p_G} - \frac{\partial TCC_G}{\partial p_G} \tag{4}$$

A.1. Optimal TAX

Deriving the components of the change in welfare, we have

$$\frac{\partial GR_G^{TAX}}{\partial p_G} = E_G + (p_G - p)\frac{\partial E_G}{\partial p_G} + \frac{\partial p}{\partial p_G}(a_G - E_G) = E_G - z_G(p_G - p) - \frac{z_G}{z_R}(a_G - E_G),$$

$$\partial B_G^{TAX} / \partial p_G = \delta(1-\beta)(-\partial E_G / \partial p_G) = z_G \delta(1-\beta).$$

Recalling that marginal abatement costs are equalized with the domestic emissions price,

$$\frac{\partial TCC_G^{TAX}}{\partial p_G} = \left(-TAC' - p\right)\frac{\partial E_G}{\partial p_G} + (A_R - E_R)\frac{\partial p}{\partial p_G} = (p_G - p)z_G - (A_R - E_R)\frac{z_G}{z_R}.$$

Substituting and solving for p_G,

$$\begin{aligned}
\frac{\partial \Delta W_G^{TAX}}{\partial p_G} &= \frac{\partial B_G^{TAX}}{\partial p_G} + \gamma \frac{\partial GR_G^{TAX}}{\partial p_G} - \frac{\partial TCC_G^{TAX}}{\partial p_G} \\
&= \delta\left(1-\beta\right) z_G + \gamma\left(E_G + \frac{z_G}{z_R}(E_G - a_G) - z_G(p_G - p) \right) - (p_G - p)z_G + \frac{z_G}{z_R}(A_R - E_R) = 0
\end{aligned}$$

$$(p_G - p)(1+\gamma) = \delta\left(1-\beta\right) + \gamma\left(\frac{E_G}{z_G} + \frac{1}{z_R}(E_G - a_G) \right) + \frac{1}{z_R}(A_R - E_R)$$

$$p_G = p + \frac{1}{1+\gamma}\delta\left(1-\beta\right) + \frac{\gamma}{1+\gamma}\left(\frac{E_G}{z_G} + \frac{(E_G - a_G)}{z_R} \right) + \frac{1}{1+\gamma}\frac{(A_R - E_R)}{z_R}$$

A.2. Optimal KILL

Recalling that $\partial k / \partial p_G = z_G + z_R$,

$$\partial GR_G^{KILL} / \partial p_G = (a_G - k) - p_G \partial k / \partial p_G = (a_G - k) - p_G (z_G + z_R).$$

$$\partial B_G^{KILL} / \partial p_G = \delta\left(\partial k / \partial p_G + (1-\beta)\partial E_R / \partial p_G\right) = \delta(z_G + \beta z_R).$$

Recalling also that $TAC' = p_G$, and $XC_G^{KILL} = p_G(E_G - (A_G - k)) = p_G(A_R - E_R)$,

$$\partial TCC_G^{KILL} / \partial p_G = TAC'(E_G^0 - E_G)z_G + A_R - E_R + p_G z_R = p_G(z_G + z_R) + A_R - E_R .$$

Thus,

$$\begin{aligned}
\frac{\partial \Delta W_G^{KILL}}{\partial p_G} &= \frac{\partial B_G^{KILL}}{\partial p_G} + \gamma \frac{\partial GR_G^{KILL}}{\partial p_G} - \frac{\partial TCC_G^{KILL}}{\partial p_G} \\
&= \delta(z_G + \beta z_R) + \gamma(a_G - k) - \gamma p_G (z_G + z_R) - (A_R - E_R) - p_G(z_G + z_R) \\
&= \delta(z_G + \beta z_R) + \gamma(a_G - k) - (A_R - E_R) - (1+\gamma)(z_G + z_R) p_G = 0 \\
p_G &= \frac{\delta\left(z_G + \beta z_R\right)}{(1+\gamma)(z_G + z_R)} + \frac{\gamma}{(1+\gamma)} \frac{(a_G - k)}{(z_G + z_R)} - \frac{(A_R - E_R)}{(1+\gamma)(z_G + z_R)} \\
&= \frac{1}{1+\gamma}\left(\delta - \frac{\delta(1-\beta) z_R}{(z_G + z_R)} + \gamma \frac{(a_G - k)}{(z_G + z_R)} - \frac{(A_R - E_R)}{(z_G + z_R)} \right)
\end{aligned}$$

A.3. Optimal BILL

A.3.1. Derivation of *BILL* price change

From $p = p_G E_G / (A - E_R)$:

$$\begin{aligned}
(A - E_R) p &= p_G E_G \\
(A - E_R) dp - p \frac{\partial E_R}{\partial p} dp &= dp_G E_G + p_G \frac{\partial E_G}{\partial p_G} dp_G \\
(A - E_R) dp + \frac{E_G}{A - E_R} p_G z_R dp &= dp_G E_G - p_G z_G dp_G \\
\left((A - E_R)^2 + E_G p_G z_R\right) dp &= dp_G \left(E_G - p_G z_G\right)(A - E_R) \\
\frac{dp}{dp_G} &= \frac{(A - E_R)\left(E_G - p_G z_G\right)}{(A - E_R)^2 + E_G p_G z_R} \\
&= \frac{\phi\left(1 - p_G z_G / E_G\right)}{\phi^2 + p_G z_R / E_G} < 1
\end{aligned}$$

A.3.2. Derivation of *BILL* trade costs

Simplifying the trade costs and using the revised emissions compliance constraint, $(p_G - p)E_G = p(A - E_R - E_G)$, we confirm that

$$\begin{aligned} XC_G^{BILL} &= p_G E_G - pa_G - p(A_G - a_G) \\ &= p_G E_G - pA_G \\ &= (p_G - p)E_G - p(A_G - E_G) \\ &= p(A - E_R - E_G) - p(A_G - E_G) \\ &= p(A_R - E_R). \end{aligned}$$

A.3.3. Derivation of *BILL* welfare change

For the components of the welfare function,

$$\frac{\partial GR_G^{BILL}}{\partial p_G} = a_G \frac{\partial p}{\partial p_G}$$

$$\frac{\partial B_G^{BILL}}{\partial p_G} = -\delta \frac{\partial E_G}{\partial p_G} - \delta\beta \frac{\partial E_R}{\partial p}\frac{\partial p}{\partial p_G} = \delta z_G + \delta\beta z_R \frac{\partial p}{\partial p_G}$$

$$\begin{aligned} \frac{\partial TCC_G^{BILL}}{\partial p_G} &= -TAC_G \frac{\partial E_G}{\partial p_G} - p\frac{\partial E_R}{\partial p}\frac{dp}{dp_G} + \frac{dp}{dp_G}(A_R - E_R) \\ &= z_G p_G + (z_R p + A_R - E_R)\frac{dp}{dp_G} \end{aligned}$$

Welfare-maximizing price:

$$\begin{aligned} \frac{\partial \Delta W_G^{BILL}}{\partial p_G} &= \frac{\partial B_G^{BILL}}{\partial p_G} + \gamma \frac{\partial GR_G^{BILL}}{\partial p_G} - \frac{\partial TCC_G^{BILL}}{\partial p_G} \\ &= \delta z_G + \delta\beta z_R \frac{dp}{dp_G} + \gamma a_G \frac{dp}{dp_G} - z_G p_G - (z_R p + A_R - E_R)\frac{dp}{dp_G} \\ &= (\delta - p_G) z_G + \big((\delta\beta - p) z_R + \gamma a_G - (A_R - E_R)\big)\frac{dp}{dp_G} \end{aligned}$$

As an intermediate step, it can be interesting to note

$$p_G = \delta + \left((\delta\beta - p)\frac{z_R}{z_G} + \gamma\frac{a_G}{z_G} - \frac{(A_R - E_R)}{z_G} \right)\frac{dp}{dp_G}$$

The remainder is derived in Mathematica, substituting the expressions for p and dp/dp_G, setting equal to zero, and solving, recalling that $\phi = (A - E_R) / E_G$.

$$
\begin{aligned}
\omega &= \frac{(A-E_R)^2}{(A-E_R)A_G + E_G(E_G - \gamma a_G) z_R / z_G + z_R \delta(\beta(A-E_R) - E_G)} \\
&= \frac{(A-E_R)^2 / E_G}{(A-E_R)A_G / E_G + (E_G - \gamma a_G) z_R / z_G + z_R \delta(\beta(A-E_R)/E_G - 1)} \\
&= \frac{(A-E_R)\phi}{\phi A_G + (E_G - \gamma a_G) z_R / z_G + z_R \delta(\beta\phi - 1)}
\end{aligned}
$$

Appendix B. Algebraic summary of numerical model

This appendix provides an algebraic summary of the equilibrium conditions for a numerical partial equilibrium model designed to investigate the implications of alternative unilateral emissions price floor strategies in a multilateral emissions trading system (ETS). The model is based on regional marginal abatement cost functions (polynomials of degree three) that can be calibrated to empirical observation of country-specific emissions abatement possibilities.

Cast as a planning problem, the model corresponds to a nonlinear program that seeks a cost-minimizing abatement scheme via emissions trading subject to country-specific initial emissions allocations, mandated reduction requirements, and unilateral emissions pricing strategies to achieve some targeted domestic CO_2 price level. The alternative pricing strategies are (1) additional domestic CO_2 taxes (scenario *TAX*) on top of the prevailing ETS price, (2) the invalidation of emissions allowances (scenario *KILL*), and (3) overcompliance requirements for domestic firms, which must surrender multiple allowances per ton of emissions (scenario *BILL*). The optimization problem can be interpreted as a market equilibrium problem where prices and quantities are defined using duality theory. In this case, a system of (weak) inequalities and complementary slackness conditions replace the minimization operator, yielding a so-called mixed complementarity problem (see, e.g., Rutherford 1995). The economic equilibrium features complementarity between equilibrium variables and equilibrium conditions. The model is implemented in GAMS (Brooke et al. 1987) using PATH (Dirkse and Ferris 1995) as a solver.

Table B.1 lists the variables and parameters employed for the algebraic model formulation. The index *r* refers to regions and the set *R* denotes those regions that adopt a unilateral pricing strategy.

Table B.1. Variables and parameters

	Variables
d_r	Emissions abatement by region *r*
p_{ETS}	ETS allowance price
μ	Scaling factor on target abatement for unilaterally acting jurisdiction(s) in scenario *KILL*
σ_r	Overcompliance ratio for unilaterally acting jurisdiction(s) in scenario *BILL*
τ_r	Emissions tax for unilaterally acting jurisdiction(s) in scenario *TAX*
	Parameters
a_{1r}, a_{2r}, a_{3r}	Coefficients of marginal abatement cost function for region *r*
t_r	Emissions reduction target for region *r*
$\bar{q}_r$	Initial (business-as-usual) emissions for region *r*
p_{ETS}^{min}	Minimum ETS allowance price
p_r	Targeted domestic emissions price for unilaterally action region(s) *r* ($r \in R$)

The equilibrium conditions for the algebraic model are as follows:

1. The zero-profit condition determines abatement d_r in region *r*:

$$a_{1r} \cdot d_r + a_{2r} \cdot d_r^2 + a_{3r} \cdot d_r^3 \geq p_{ETS} \cdot \rho_r + \tau_r$$

2. The market clearance for emissions in ETS determines the ETS allowance price p_{ETS} :

$$\sum_r \left(\bar{q}_r - t_r \cdot \left(1 + \mu|_{r \in R} \right) \right) \geq \sum_r \left(\sigma_r \cdot \left(\bar{q}_r - d_r \right) \right)$$

3. The lower bound on the ETS price determines the scaling factor on target abatement for unilaterally acting jurisdiction in scenario *KILL*

$$p_{ETS} \geq \mathrm{p}_{\mathrm{ETS}}^{\min}$$

4. The domestic target price p_r constraint determines the overcompliance ratio σ_r to domestic emissions for unilaterally acting jurisdiction in scenario *BILL*:

$$\sigma_r \cdot p_{ETS} \geq \mathrm{p}_r$$

5. The domestic target price p_r constraint determines the CO_2 tax τ_r in scenario *TAX*:

$$p_{ETS} + \tau_r \geq \mathrm{p}_r$$

Table B.2. Coefficients of marginal abatement cost curves

	a_{1r}	a_{2r}	a_{3r}
Germany	0.23005451	-0.00041771	0.00000746
United Kingdom	0.49014837	-0.00026727	0.00007333
France	0.94403862	-0.00220837	0.00047037
Netherlands	1.08747496	0.00209384	0.00064114
Austria	4.75281828	0.09817312	0.03086963
Sweden	9.19342635	0.46732731	0.20001664
Rest of EU	0.09102146	-0.00015097	0.00000075

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