Combining Price and Quantity Controls under Partitioned Environmental Regulation

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Abstract

This paper analyzes hybrid emissions trading systems (ETS) under partitioned environmental regulation when firms' abatement costs and future emissions are uncertain. We show that hybrid policies that introduce bounds on the price or the quantity of abatement provide a way to hedge against differences in marginal abatement costs across partitions. Price bounds are more efficient than abatement bounds as they also use information on firms' abatement technologies while abatement bounds can only address emissions uncertainty. Using a numerical stochastic optimization model with equilibrium constraints for the European carbon market, we find that introducing hybrid policies in EU ETS reduces expected excess abatement costs of achieving targeted emissions reductions under EU climate policy by up to 89 percent. We also find that under partitioned regulation there is a high likelihood for hybrid policies to yield sizeable ex-post cost reductions.

Keywords: Emissions trading, Partitioned environmental regulation, Uncertainty, Prices, Quantities, EU ETS
JEL: H23, Q54, C63

1. Introduction

Environmental regulation of an uniformly dispersed pollutant such as carbon dioxide (CO_2) is often highly fragmented as regulators employ different instruments for different sources and emitters. A prominent example for partitioned environmental regulation is the European Union (EU)'s climate policy under which the overall emissions reduction target is split between sources covered by the EU Emissions Trading System and sources regulated on the member state level.[3] Major policy choices under partitioned environmental regulation involve choosing the instrument for each partition and determining how the overall environmental target is split between the partitions. Making these choices *ex-ante*, i.e. before firms' abatement

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[3]The EU Emissions Trading System 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 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 promotion and technology policies and other command-and-control measures. Taken together, this is expected to deliver a reduction in EU-wide emissions of 14% relative to 2005 (which is equivalent to a 20% reduction relative to 1990 levels).

costs and future emissions are known by the regulator, means that the *ex-post* marginal abatement costs will in all likelihood not be equalized across all polluting sources. Given the considerable uncertainties about future abatement technologies and output (and hence emissions) germane to practical policymaking, partitioned environmental regulation thus inherently faces the problem of achieving a given environmental target at lowest possible costs.

This paper analyzes hybrid emissions trading systems (ETS) with bounds on the price or the quantity of abatement when environmental regulation is partitioned. We ask whether and how the ex-ante and ex-post abatement costs of partitioned climate regulation that is based on an ETS can be reduced by combining price and quantity controls. We have in mind a situation in which the regulator has to decide ex ante on the allocation of a given environmental target between an ETS and non-ETS partition and on the introduction of lower and upper bounds on the permit price or the quantity of abatement in the ETS partition. Although partitioned regulation seems to be the rule rather than the exception in the domain of real-world environmental policies, the fundamental public policy question of combining price and quantity controls—going back to the seminal contributions by Weitzman (1974) and Roberts & Spence (1976)—has so far abstracted from the important complexity of partitioned regulation.

The introduction of price or abatement bounds in an ETS provides a way to hedge against differences in the marginal abatement costs across the partitions of environmental regulation when some of the abatement burden is reallocated based on actual (i.e., ex-post) abatement costs. Importantly, this can enhance the cost-effectiveness of partitioned environmental regulation by moving the system closer to a first-best outcome in which all emitters face identical marginal abatement costs (MACs). We theoretically characterize ex-ante optimal hybrid ETS policies with price or abatement bounds and show that it can be optimal to allow expected MACs to differ across sectors. We further show that from an ex-ante perspective hybrid policies can never increase the costs of partitioned environmental regulation.

We complement our theoretical analysis of hybrid policies under partitioned environmental regulation with an empirical analysis of EU climate policy investigating the question to what extent introducing hybrid policies in the EU ETS could lower the costs of achieving EU's emissions reduction goals. To this end, we develop a numerical stochastic policy optimization model with equilibrium constraints for the European carbon market that is calibrated based on empirical MAC curves derived from a numerical general equilibrium model. The model incorporates two important sources of firm-level uncertainties in the ETS and non-ETS sectors that are relevant for the policy design problem of carbon mitigation: (1) uncertainty about future "no policy intervention" emissions, reflecting uncertain output, demand, or macroeconomic shocks, and (2) uncertainty about future abatement technologies.

We find that hybrid ETS policies yield substantial savings in abatement costs relative to a pure quantity-based (i.e., the currently existing) EU ETS policy. Under second-best conditions, i.e. when the regulator can ex-ante choose the allocation of the emissions budget across the partitions, an optimal hybrid policy reduces the expected excess costs–relative to a hypothetical, first-best state-contingent policy–by up to 56% (or up to billion \$1.5 per year). A third-best hybrid policy, i.e. assuming an exogenously given split of the emissions budget, that reflects current EU climate policy is found to lower expected excess costs by up to 89% (or up to billion \$12.1 per year). Overall, we find, however, that the ability of hybrid policies to reduce expected abatement costs diminishes if sectoral baseline emissions exhibit a strong positive correlation. Further, we find that hybrid policies with price bounds are more effective to reduce the abatement costs than hybrid policies with abatement bounds. Price bounds are advantageous as they can address both types of risks whereas abatement bounds can only hedge against emissions uncertainty.

Our quantitative analysis suggests that hybrid policies with price bounds are highly likely to yield sizeable ex-post savings in abatement costs, depending on the correlation structure between sectoral "no intervention" emissions. If emissions are negatively (positively) correlated, the probability of ex-post costs savings is 0.67 (0.49). Hybrid polices with abatement bounds achieve ex-post cost reductions in 66 percent of cases if baseline emissions are negatively correlated, but they yield only negligible cost savings when baseline emissions are positively correlated. The reason for this is that abatement bounds fail to exploit information on firms' abatement technology.

The present paper contributes to the existing literature in several ways. First, the paper is related to the literature on ex-post efficient permit markets. As Weitzman (1974) has shown, internalizing the external effects under uncertainty about the costs of pollution control and damages (or benefits) from pollution will in general yield second-best outcomes with lower welfare as compared to an ex-post efficient, first-best solution. The relatively large literature on ex-post efficient permit markets has suggested alternative ways for hybrid regulation strategies that combine elements of permit markets and price control (Roberts & Spence, 1976; Collinge & Oates, 1982; Unold & Requate, 2001; Newell et al., 2005). By proposing to use different institutional designs, these hybrid strategies all propose in the end to implement a price-quantity relation for emissions, i.e. a supply function of emissions permits, that approximates the marginal damage function. The welfare gains of ex-post efficient hybrid regulation relative to either pure price or quantity controls have shown to be substantial (Pizer, 2002).[4] None of the existing studies, however, does consider the problem of combining prices and quantities under partitioned environmental regulation.

Second, a small number of recent papers examines the idea of introducing a quantity-based adjustment mechanism to the EU ETS (Fell, 2015; Schopp et al., 2015; Kollenberg & Taschini, 2015; Ellerman et al., 2015; Perino & 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 (EC, 2014). As long as the MSR is conceived as altering the environmental target (see, for example, Kollenberg & Taschini, 2015), it can be interpreted as a mechanism to achieve ex-post efficiency in European carbon market.[5] This interpretation, however, importantly depends on the premise that emissions reductions to reach the overall EU climate policy goal are allocated in a cost-effective manner across sources inside and outside the EU ETS (as generally pointed by Roberts & Spence, 1976). We contribute to this debate by analyzing a hybrid ETS when the environmental target is constant and the abatement burden has to be allocated across different partitions. Moreover, while the MSR represents a quantity-based adjustment mechanism, we add by comparing the ability of price- and quantity-indexed bounds to address different types of risk.

Third, the "safety valve" literature–being in fact closely related to the original proposal made by Roberts & Spence (1976)–has scrutinized the idea of introducing price bounds into a cap-and-trade system of emissions regulation to limit the costs of meeting the cap (Jacoby & Ellerman, 2004; Pizer, 2002). Hourcade & 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.[6] While the "safety valve" literature on a general level considers hybrid approaches to emissions pricing under an ETS, it does not place this issue in the context of partitioned environmental regulation.

[4]In a model of disaggregated firm behavior, Krysiak (2008) has shown that besides increasing expected social costs, hybrid policies can have indirect benefits due to reducing the consequences of imperfect competition, enhancing incentives for investment, and generating a revenue for the regulating authority.

[5]Perino & Willner (2015), in contrast, views the MSR as being allowance preserving.

[6]In fact, existing cap-and-trade systems in California, RGGI, and Australia already have introduced a price floor.

Lastly, a number of studies have quantified the efficiency costs of partitioned regulation caused by limited sectoral coverage of the EU ETS (Böhringer et al., 2006, 2014) or due to strategic partitioning (Böhringer & Rosendahl, 2009; Dijkstra et al., 2011). While this literature has importantly contributed to informing the climate policy debate about cost-effective regulatory designs, it has abstracted from uncertainty and has also not investigated the issue of combining price and quantity controls.

The remainder of the paper is organized as follows. Section 2 presents our theoretical argument and characterizes ex-ante optimal hybrid policies with price and abatement bounds under partitioned environmental regulation. Section 3 describes our quantitative, empirical framework that we use to analyze the effects of hybrid policies for carbon mitigation in the context of EU climate policy. Section 4 presents and discusses the findings from our empirical analysis. Section 5 concludes.

2. The theoretical argument

In this section, we sketch our theoretical argument for why hybrid policies which combine price and quantity controls in the context of partitioned environmental regulation may decrease expected abatement costs. The argument can be summarized as follows: consider an economy with two polluting firms where emissions from one firm are regulated under an ETS while emissions by the other firms are regulated separately to achieve an economy-wide emissions target. If the regulator is uncertain about firms' abatement costs or future emissions, pure quantity-based regulation will fail to equalize MACs between firms in most states of the world, hence undermining cost-effectiveness. Adding bounds on the permit price or the quantity of abatement in the ETS partition provides a hedge against too large differences in firms' marginal abatement costs, in turn reducing the expected abatement costs of partitioned environmental regulation.

2.1. Basic setup

Although the reasoning below fits alternative applications, we let climate change and CO_2 abatement policies guide the modeling. We have in mind a world of partitioned environmental regulation with two sets of pollution firms: one set, T, participates in an emissions trading system (ETS) while the other set, N, does not.[7] We will abstract from decision making within both sets and treat T and N as one firm or sector; in particular, we assume that abatement within a sector is distributed among firms in a cost-minimizing manner.[8]

2.1.1. Firms' abatement costs and sources of uncertainty

Firm i's abatement costs are described by the following abatement cost function: $C_i\,(a_i, g_i\,(\epsilon_i))$, where $a_i := e_i^0 + \epsilon_i - e_i$ denotes sector i's abatement defined as the difference between the "no-intervention" baseline emissions level, $e_i^0 + \epsilon_i$, and emissions after abatement e_i. Cost functions are assumed to be increasing in abatement ($\frac{\partial C_i}{\partial a_i}$). The functions g_i denote the level of the abatement technology. We assume that g_i is linear in ϵ_i with unitary slope ($\frac{\partial g_i}{\partial \epsilon_i} = 1$).[9] Costs are assumed to be decreasing in the level of the technology ($\frac{\partial C_i}{\partial g_i} < 0$). The cost functions are assumed to be strictly convex, i.e., $\frac{\partial^2 C_i}{\partial a_i^2} > 0$, $\frac{\partial^2 C_i}{\partial g_i^2} > 0$, and $\frac{\partial^2 C_i}{\partial a_i^2}\frac{\partial^2 C_i}{\partial g_i^2} > (\frac{\partial^2 C_i}{\partial a_i \partial g_i})^2$.

[7] The assignment of firms to each set is fixed and exogenously given. Caillaud & Demange (2005) analyze the optimal assignment of activities to trading and tax systems.

[8] The terms "firm" and "sector" are thus used interchangeably throughout the paper.

[9] $g_i(\cdot)$ is not strictly needed for our derivations but names the second arguments of the abatement costs function and is thus introduced for notational clarity.

ϵ_i is a random variable which captures all the relevant uncertainty about firms' abatement costs. We distinguish between technology and baseline emissions uncertainty. First, technology uncertainty arises as the regulator does not know the costs associated with reducing emissions from either substituting carbon with non-carbon inputs in production or from adjusting output (or a combination of both). Second, the regulator does not know the level of "no-intervention" emissions, beyond the certain level e_i^0, reflecting the fact that energy demand, GDP growth, and other economic conditions may affect baseline emissions but cannot be known a priori. From the definition of abatement, it follows that baseline emissions react linearly to the signal ϵ_i. Technology uncertainty reacts through the technology function $g_i(\epsilon_i)$ on the cost function. ϵ_i is distributed over compact supports $\left[\underline{b}_i, \overline{b}_i\right]$ with the joint probability distribution $f(\epsilon_T, \epsilon_N)$. We assume that $\mathbb{E}(\epsilon_i) = 0$. We do not impose any assumptions on the correlation between sectoral random variables ϵ_T and ϵ_N.

2.1.2. Policy design problem, information structure, and firm behavior

The regulator is faced with the problem of limiting economy-wide emissions at the level $\overline{e} \geq \sum_i e_i$. The major premise underlying our analysis is that regulation of emissions is partitioned: emissions from sector T only make up some fraction of total economy-wide emissions and are regulated by an ETS; sector N's emissions are not covered by the ETS.[10] The regulator has to split the emissions budget across partitions by choosing sectoral emissions targets, $\overline{e}_i$. We define the allocation factor as the amount of emissions allocated to the trading sector relative to the economy-wide emissions target: $\lambda = \overline{e}_T/\overline{e}$.

A policy that only consists of λ is referred to as a pure quantity-based approach as it solely determines the quantity of permits in the ETS and maximum amount of emissions in the non-ETS sector. The central theme of this paper is to investigate hybrid policies that enlarge the instrument space by allowing to introduce, in addition to λ, lower and upper bounds on the ETS permit price $(\underline{P}, \overline{P})$ or the amount of abatement in the ETS sector $(\underline{a}, \overline{a})$.

The regulator's problem is to minimize expected total abatement costs

$$\Psi = \mathbb{E}\left[C_T\left(\tilde{e}_T^0 - \lambda\overline{e}, g_t(\epsilon_T)\right) + C_N\left(\tilde{e}_N^0 - [1-\lambda]\overline{e}, g_n(\epsilon_N)\right)\right] \tag{1}$$

by choosing either (1) a pure quantity-based regulation (λ), (2) hybrid regulation which combines quantity and price controls ($\{\lambda, \underline{P}, \overline{P}\}$), or (3) hybrid regulation which combines quantity control with bounds on abatement ($\{\lambda, \underline{a}, \overline{a}\}$).[11]

The regulator *ex ante* chooses a policy design, i.e. before the realizations of the random variables and hence before firms' abatement cost and baseline emissions are known. It is assumed that the regulator is able to commit on this ex-ante announced regulatory scheme. The distribution and cost functions f and C_i as well as baseline emissions e_i^0 are assumed to be "common knowledge". *Ex post*, i.e. after the realizations of the random variables, firms choose their abatement. Given the price for emissions in each sector, P_i, firms choose their level of abatement by equating price with MAC, i.e. $P_i = \partial C_i(a_i, g_i)/\partial a_i \; \forall \epsilon_i$.

We assume that the environmental target is exogenous, constant, and always has to be fulfilled. Thus, if ex-ante chosen price or abatement bounds become binding *ex post*, sectoral emissions targets are adjusted to ensure that the economy-wide emissions target is met.

[10] We assume that emissions control in sector N is achieved in a cost-effective way.

[11] As we seek to characterize (optimal) policy designs which achieve an exogenously set overall emissions target, we abstract here from explicitly including the benefits from averted pollution.

2.2. *First-best policies*

In an environment of complete knowledge and perfect certainty there is a formal identity between the use of prices and quantities as policy instruments. If there is any advantage to employing some forms of hybrid price and quantity control modes, therefore, it must be due to inadequate information or uncertainty. A useful reference point is thus to define the first-best optimal policy when state-contingent policies are feasible.

The first-best quantity control, $\lambda^*(\epsilon_T, \epsilon_N)$, and price control, $P^*(\epsilon_T, \epsilon_N)$, are in the form of an entire schedule and functions of the random variables ϵ_T and ϵ_N equalizing MACs among sectors in all possible states. Thus, $\lambda^*(\epsilon_T, \epsilon_N)$ and $P^*(\epsilon_T, \epsilon_N)$ are implicitly defined by

$$\begin{aligned} P^*(\epsilon_T, \epsilon_N) &= \frac{\partial C_T\left(e_T^0 + \epsilon_T - \lambda^*(\epsilon_T, \epsilon_N)\overline{e}, g_T(\epsilon_T)\right)}{\partial a_T} \\ &= \frac{\partial C_N\left(e_N^0 + \epsilon_N - (1 - \lambda^*(\epsilon_T, \epsilon_N))\overline{e}, g_N(\epsilon_N)\right)}{\partial a_N}. \end{aligned} \tag{2}$$

It should be readily apparent that it is infeasible for the regulator to transmit an entire schedule of ideal price or quantity controls. A contingency message is a complicated, specialized contract which is expensive to draw up and hard to understand. The remainder of this paper therefore focuses on policies that cannot explicitly be made state-contingent.

2.3. *Pure quantity controls*

In the presence of uncertainty, price and quantity instruments transmit policy control in quite different ways. Before turning to hybrid price-quantity policies, we first provide some basic intuition for a pure quantity-based policy in the context of partitioned environmental regulation.

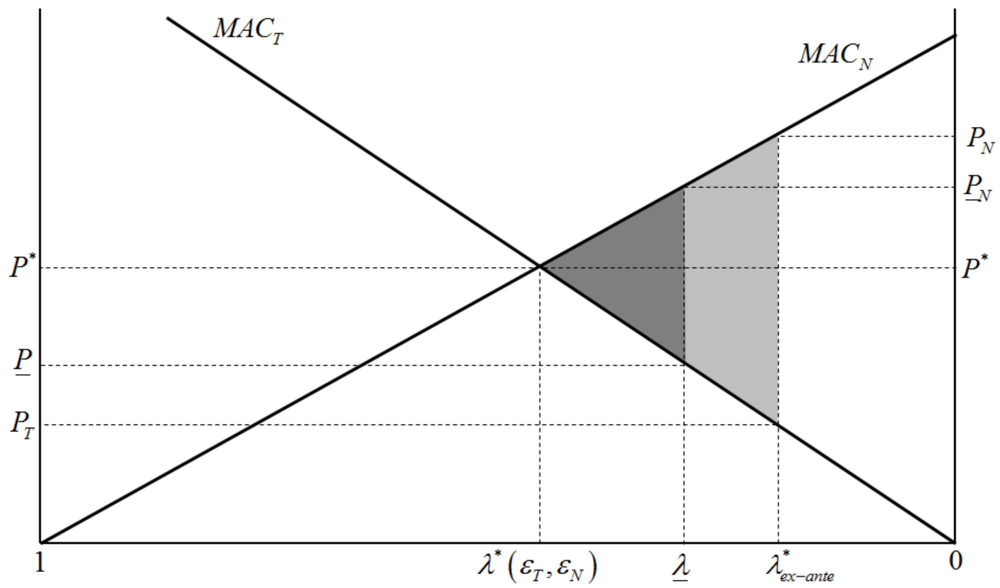
What is the ex-ante optimal allocation of the economy-wide emissions target among sectors if λ cannot be conditioned on ϵ_T and ϵ_N? The optimal condition of the policy decision problem in (1) by choosing only the allocation factor is given as:

$$\mathbb{E}\left[\frac{\partial C_T\left(e_T^0 + \epsilon_T - \lambda^*_{\textit{ex-ante}}\overline{e}, g_T(\epsilon_T)\right)}{\partial a_T}\right] = \mathbb{E}\left[\frac{\partial C_N\left(e_N^0 + \epsilon_N - (1 - \lambda^*_{\textit{ex-ante}})\overline{e}, g_N(\epsilon_N)\right)}{\partial a_N}\right]. \tag{3}$$

Thus, under a pure quantity approach the ex-ante optimal allocation factor $\lambda^*_{\textit{ex-ante}}$ is chosen such that *expected* MACs among sectors are equalized.

Given incomplete information about firms' abatement costs and baseline emissions at the time the regulator chooses λ, in all likelihood $\lambda^*_{\textit{ex-ante}} \neq \lambda^*(\epsilon_T, \epsilon_N)$ which implies that MACs among sectors are not equalized *ex post*. Figure 1 illustrates this situation by depicting *ex-post* sectoral MAC functions, $\lambda^*_{\textit{ex-ante}}$, and $\lambda^*(\epsilon_T, \epsilon_N)$ for a given environmental target. Total abatement costs are minimized if the abatement burden is partitioned according to the state-contingent policy functions λ^* or P^*. It is apparent from $\lambda^*_{\textit{ex-ante}} \neq \lambda^*(\epsilon_T, \epsilon_N)$ that the *realized* carbon prices in sectors T and N, denoted, respectively, by P_T and P_N differ. The excess abatement costs, i.e., change in abatement costs relative to a first-best policy with state-contingent instruments, are equal to the sum of the two gray-shaded areas in Figure 1. Excess costs arise because of the uncertainty about firms' abatement cost. Intuitively, ex-ante policy designs capable of hedging against "too large" differences in *ex-post* sectoral MACs can reduce expected total abatement costs and may even lead to lower *ex-post* abatement costs when compared to pure quantity-based environmental regulation. This fundamental insight provides the starting point for investigating hybrid policy designs.

Figure 1: Abatement costs of partitioned environmental regulation under "first-best" [$\lambda^*(\epsilon_T, \epsilon_N)$, $P^*(\epsilon_T, \epsilon_N)$], "second-best" pure quantity-based [$\lambda^*_{ex\text{-}ante}$] and hybrid [$\underline{\lambda}$] policies



2.4. *Ex-post effects of price and abatement bounds*

To derive our results on *ex ante* optimal policy designs when the regulator can choose the allocation factor as well as bounds on the permit price ($\{\lambda, \underline{P}, \overline{P}\}$) or on the level of abatement in the T sector ($\{\lambda, \underline{a}, \overline{a}\}$), it is helpful to first develop some intuition for the possible *ex-post* outcomes.

Consider first the case of price bounds. Given realizations of ϵ_T and ϵ_N, three cases are possible. First, if price bounds are not binding, the outcome under a hybrid policy is identical to the one under a pure quantity control. Second, the price floor binds. Given that the economy-wide emissions target is constant and has to be fulfilled, the emissions target in the T sector has to adjust downward thus shifting an equal amount of emission allowances to the N sector. Third, the price ceiling binds, in which case the abatement requirement in the the T (N) sector has to decrease (increase). It is thus straightforward to see that the *ex-post* allocation factor is a function of the state variables ϵ_T and ϵ_N. The difference to a first-best policy is, however, that λ cannot be fully conditioned on ϵ_T and ϵ_N; it can rather only be indirectly controlled through the *ex ante* choice of price bounds.

To see why adding price bounds to a pure quantity-based control scheme can lower abatement costs in a second-best world, consider again Figure 1. Assume that the regulator has chosen $\lambda^*_{ex\text{-}ante}$ and a price floor $\underline{P}$. Under pure quantity control (ignoring $\underline{P}$) this would lead to the emissions prices P_T and P_N. If the price in the T sector realizes below the price floor ($P_T < \underline{P}$), the price bound binds with the consequence that abatement in the T sector needs to increase in order to increase the price. The abatement in the N sector therefore has to decline to ensure that the economy-wide emissions target holds, which is achieved by adjusting the allocation factor to $\underline{\lambda}$. As abatement in the N sector decreases, the carbon price in this sector declines from P_N to $\underline{P}_N$. For the case depicted in Figure 1, the introduction of a price floor therefore moves sectoral carbon prices, and hence, sectoral MACs closer to the first-best, uniform carbon price $P^*(\epsilon_T, \epsilon_N)$. The hybrid policy therefore decreases the costs of second-best regulation by the light gray-shaded area. A similar argument can be constructed for any price ceiling above the first-best optimal emissions price.

If the regulator imposes a bound on the minimum amount of abatement, the *ex post* effect is similar to the one under a minimum permit price bound. To see this, consider the case where the regulator have chosen a binding lower abatement bound such that $\underline{a} = e_T^0 \underline{\lambda} \overline{e}$. This triggers the same *ex post* adjustment in sectoral emissions budgets as with a binding price floor. Hence the savings in total abatement cost are identical. Following the same reasoning, in Figure 1 a binding upper bound on abatement is similar to the case of a binding price ceiling.

Proposition 1. *Consider an economy with polluting firms i that are partitioned in two sectors $i \in \{T, N\}$. Sectoral abatement cost functions are strictly convex in abatement, and environmental policy is concerned with limiting economy-wide emissions at the level $\overline{e}$. Each partition is regulated separately with respective targets $\overline{e}_T$ and $\overline{e}_N$ that are pre-determined given the allocation factor $\lambda = \overline{e}_T / \overline{e}$. Then, introducing bounds on the permit price or quantity of abatement weakly decreases economy-wide abatement costs*

(a) if the lower (upper) bound on the emissions price in one partition is smaller (greater) or equal to the optimal permit price P^*, or

(b) if the lower (upper) bound on the amount of abatement in one partition is smaller (greater) or equal to the optimal abatement level $e_T^0 - \lambda^* \overline{e}$.

Proof. See Appendix A. □

Proposition 1 bears out a fundamental insight: under partitioned environmental regulation and given that the environmental target is fixed and always has to be met, economy-wide abatement costs cannot increase as long as the permit price floor (ceiling) is set below (above) or equal to the *ex post* optimal environmental tax. Consider the example of a price floor: if the initially chosen allocation factor λ was too low, i.e. abatement in the ETS sector is sub-optimally high, then the permit price exceeds the optimal level but the price floor will not be binding. Total abatement costs will therefore not be not affected. If, however, the allocation factor was initially set too high, the *ex post* re-allocation of sectoral emissions targets following the introduction of a binding price floor will decrease total abatement cost. Importantly, Proposition 1 implies that in a policy environment with partitioned regulation, if the regulator has access to an estimate of the optimal permit price—or equivalently an optimal amount of abatement—in *one* of the sectors, a hybrid policy that introduces bounds on the permit price or on the permissible amount of abatement together with a mechanism that adjusts sectoral environmental targets under an economy-wide constant target decreases economy-wide abatement costs.

2.5. Ex-ante optimal policies with price bounds

This section characterizes *ex-ante* optimal hybrid policies with price bounds. It is useful to re-write total expected abatement costs in (1) in a way that differentiates between situations in which emissions price bounds are binding or non-binding:[12]

$$\begin{aligned}\Psi\left(\lambda, \underline{P}, \overline{P}\right) = & \,\mathbb{E}\left[\sum_i C_i\left(e_i^0 + \epsilon_i - \lambda_i \overline{e}, g_i(\epsilon_i)\right) \middle| \underline{\epsilon}(\lambda, \underline{P}) < \epsilon_T < \overline{\epsilon}\left(\lambda, \overline{P}\right)\right] \\ & + \mathbb{E}\left[\sum_i C_i\left(e_i^0 + \epsilon_i - \underline{\lambda}_i(\lambda, \underline{P})\,\overline{e}, g_i(\epsilon_i)\right) \middle| \epsilon_T \leq \underline{\epsilon}(\lambda, \underline{P})\right] \\ & + \mathbb{E}\left[\sum_i C_i\left(e_i^0 + \epsilon_i - \overline{\lambda}_i\left(\lambda, \overline{P}\right)\overline{e}, g_i(\epsilon_i)\right) \middle| \overline{\epsilon}\left(\lambda, \overline{P}\right) \leq \epsilon_T\right] \qquad (4)\end{aligned}$$

[12]Throughout the analysis we assume an interior solution for λ.

where we introduced sector-specific allocation factors λ_i defined as $\lambda_T := \lambda$ and $\lambda_N = 1-\lambda_T$ (with equivalent definitions for $\underline{\lambda}_i$ and $\overline{\lambda}_i$).

The first line in (4) refers to the case when price bounds are non-binding. The second and third line refer to cases in which the price floor or ceiling is binding, respectively. For any *ex-ante* chosen λ and price bounds in sector T, there exist cutoff levels for realizations of sector T's random variable, $\underline{\epsilon}(\lambda, \underline{P})$ and $\overline{\epsilon}\left(\lambda, \overline{P}\right)$, at which the price floor and ceiling on the emissions price are binding. If either price bound is binding, the allocation factor has to adjust *ex post* to ensure that the economy-wide emissions target is achieved. These endogenous allocation factors are denoted $\underline{\lambda}(\lambda, \underline{P})$ and $\overline{\lambda}\left(\lambda, \overline{P}\right)$, respectively.

The policy problem in (4) is equivalent to the one in (1) if price bounds are non-binding, i.e. the regulators could choose a price floor equal to zero and a sufficiently large price ceiling such that it never becomes binding. In such a case the expected total abatement cost function (4) is equivalent to the expected abatement cost function under pure quantity control (1). The regulator's problem of choosing the policy $\{\lambda, \underline{P}, \overline{P}\}$ thus includes the case of a pure quantity-based regulation.

Proposition 2. *Expected total abatement costs under a hybrid environmental policy with emissions price bounds cannot be larger than those under pure quantity-based policy.*

Proof. This follows from comparing the regulator's policy design problems in (4) and (1) and noting that it is always possible to choose the price floor and ceiling such they are never binding. Thus, (4) is a relaxed problem of (1) and costs can never increase as compared to a pure quantity-based regulation scheme. □

2.5.1. Cutoff levels and endogenous allocation factor

The hybrid policy only differs from a pure quantity control, if there exist states of the world in which price bounds are binding. We thus need to describe how the cutoff levels for the random variable in the ETS sector, $\underline{\epsilon}(\lambda, \underline{P})$ and $\overline{\epsilon}\left(\lambda, \overline{P}\right)$, and the cutoff levels for the allocation factor, $\underline{\lambda}(\lambda, \underline{P})$ and $\overline{\lambda}\left(\lambda, \overline{P}\right)$ depend on policy choice variables. If the price floor is binding, cost-minimizing behavior of firms requires that marginal abatement costs equal the permit price at the bound. The lower cutoff level for ϵ_T and λ are implicitly defined by:[13]

$$\frac{\partial C_T\left(e_t^0 + \underline{\epsilon}(\lambda, \underline{P}) - \lambda\overline{e}, g_T\left(\underline{\epsilon}(\lambda, \underline{P})\right)\right)}{\partial a_T} = \underline{P} \Rightarrow \underline{\epsilon}(\lambda, \underline{P}) \tag{5a}$$

$$\frac{\partial C_T\left(e_t^0 + \epsilon - \underline{\lambda}(\lambda, \underline{P})\,\overline{e}, g_T(\epsilon)\right)}{\partial a_T} = \underline{P} \Rightarrow \underline{\lambda}(\lambda, \underline{P})\ . \tag{5b}$$

Partially differentiate (5a) and (5b) with respect to policy choice variables to obtain:[14]

$$\frac{\partial\underline{\lambda}}{\partial\underline{P}} = \frac{\partial\overline{\lambda}}{\partial\overline{P}} = -\frac{1}{\overline{e}}\underbrace{\left(\frac{\partial^2 C_T}{\partial a_T^2}\right)^{-1}}_{\text{reallocation effect}} =: -\frac{\omega_R}{\overline{e}} \tag{6a}$$

[13]Upper cutoff levels for ϵ and λ are defined correspondingly but are not shown for reasons of brevity.

[14]Changing λ has no impact on the cutoff level for λ as every change in the *ex ante* allocation factor is *ceteris paribus* compensated for by an offsetting change due to adjusting sectoral targets *ex post*. Thus, $\partial\underline{\lambda}/\partial\lambda = \partial\overline{\lambda}/\partial\lambda = 0$ is omitted from the equations below.

$$\frac{\partial \underline{\epsilon}}{\partial \underline{P}} = \frac{\partial \overline{\epsilon}}{\partial \overline{P}} = \Bigg(\underbrace{\underbrace{\frac{\partial^2 C_T}{\partial a_T^2}}_{\text{emissions uncertainty}} + \underbrace{\frac{\partial^2 C_T}{\partial a_T \partial g_T}}_{\text{technology uncertainty}}}_{\text{uncertainty effect}} \Bigg)^{-1} =: \omega_U \tag{6b}$$

$$\frac{\partial \underline{\epsilon}}{\partial \lambda} = \frac{\partial \overline{\epsilon}}{\partial \lambda} = \frac{\omega_U}{\omega_R} \overline{e} \,. \tag{6c}$$

Equation (6a) reflects that a change in the (binding) price bound triggers a reallocation of abatement across sectors to hold the overall environmental target $\overline{e}$. The magnitude of this effect depends, besides $\overline{e}$, on the slope of the MAC curve with respect to abatement which we define as $\omega_R > 0$ or the *reallocation effect*. As MACs are strictly convex in abatement, it follows that $\omega_R > 0$. The steeper the MAC curve, the more the cutoff level changes, in turn implying a larger shift of emissions targets between sectors.

Equation (6b) shows that the reaction of the cutoff levels for ϵ with respect to the price bounds depend on the slope of the MAC curve with respect to ϵ. Terms in brackets on the RHS indicate the change in the MAC as the threshold level changes due to affecting baseline emissions and abatement technology (i.e. through the first and second arguments of $C(\cdot)$). We define the combined effect as the *uncertainty effect*, denoted by ω_U. ω_U is the larger, the less strongly MAC react to changes in ϵ. The sign of ω_U is ambiguous. If there is no technology uncertainty, $\omega_U = \omega_R$, and hence $\omega_U > 0$. With technology uncertainty, and if $\frac{\partial^2 C_T}{\partial a_T \partial g_T} > 0$, ω_U is the smaller the stronger emissions or technology uncertainty affect the MAC. A large influence of emissions uncertainty on the MAC does not necessarily mean that ω_U is small as technology uncertainty can negatively impact the MAC (i.e. $\frac{\partial^2 C_T}{\partial a_T \partial g_T} < 0$).

Lastly, equation (6c) shows that changing λ affects the cutoff levels for ϵ in two ways. First, similar to the case of a price bound, there exists an *uncertainty effect*. For a given change in λ, the impact on the cutoff level is the larger, the smaller is the slope of the MAC with respect to ϵ. Second, an additional *reallocation effect* arises because changing λ changes how the economy-wide emissions target $\overline{e}$ is allocated across sectors.

2.5.2. First-order conditions and interpretation

Expected total abatement costs are minimized when the partial derivatives in (4) with respect to λ, $\underline{P}$, and $\overline{P}$ are zero, or when the following conditions hold:[15]

$$\begin{aligned} \lambda: \quad & \mathbb{E}\left[\frac{\partial C_T}{\partial a_T}\middle| \underline{\epsilon} \le \epsilon_T \le \overline{\epsilon}\right] + \frac{\omega_U}{\omega_R}\bigg|_{\underline{\epsilon}} \underline{P} + \frac{\omega_U}{\omega_R}\bigg|_{\overline{\epsilon}} \overline{P} = \mathbb{E}\left[\frac{\partial C_N}{\partial a_N}\middle| \underline{\epsilon} \le \epsilon_T \le \overline{\epsilon}\right] \\ & + \frac{\omega_U}{\omega_R}\bigg|_{\underline{\epsilon}} \mathbb{E}\left[\frac{\partial C_N}{\partial a_N}\middle| \epsilon_T = \underline{\epsilon}\right] \\ & + \frac{\omega_U}{\omega_R}\bigg|_{\overline{\epsilon}} \mathbb{E}\left[\frac{\partial C_N}{\partial a_N}\middle| \epsilon_T = \overline{\epsilon}\right] \end{aligned} \tag{7a}$$

$$\begin{aligned} \underline{P}: \quad & \mathbb{E}\left[\omega_R \middle| \epsilon_T \le \underline{\epsilon}\right] \underline{P} + \omega_U|_{\underline{\epsilon}} \underline{P} = \mathbb{E}\left[\omega_U \frac{\partial C_N}{\partial a_N}\middle| \epsilon_T \le \underline{\epsilon}\right] \\ & + \omega_U|_{\underline{\epsilon}} \mathbb{E}\left[\frac{\partial C_N}{\partial a_N}\middle| \epsilon_T = \underline{\epsilon}\right] \end{aligned} \tag{7b}$$

[15] See Appendix D for the derivations.

$$\overline{P}: \quad \mathbb{E}\left[\omega_R \middle| \epsilon_T \leq \overline{\epsilon}\right]\overline{P} + \omega_U|_{\overline{\epsilon}}\,\overline{P} = \mathbb{E}\left[\omega_R \frac{\partial C_N}{\partial a_N}\middle| \epsilon_T \leq \overline{\epsilon}\right] + \omega_U|_{\overline{\epsilon}}\,\mathbb{E}\left[\frac{\partial C_N}{\partial a_N}\middle| \epsilon_T = \overline{\epsilon}\right]. \tag{7c}$$

Equation (7a) implicitly defines the *ex-ante* optimal fulfillment factor. Fundamentally, the optimal choice of λ still involves equating expected MACs between the two partitions. The difference compared to the case with a pure quantity control is, however, that expected marginal costs now comprise additional terms that reflect the marginal costs of changing λ when using price controls. The first terms on the LHS and RHS of equation (7a) represent MAC for sector T and N, respectively, in the case that none of the price bounds are binding. The second and third terms reflect marginal costs from switching from an ETS system to a system of price controls.[16]

Proposition 3. *The ex-ante optimal hybrid policy with price bounds under partitioned regulation allocates the overall environmental target such that the expected marginal abatement costs across partitions differ in all likelihood in the range where price bounds are not binding.*

Proof. Follows from the first-order condition (7a) and noting that for a non-trivial hybrid policy, i.e. one under which there exist realizations for ϵ such that *ex-ante* chosen price bounds are binding, the second and third terms on the LHS and RHS of (7a) are non-zero. □

These additional terms on the LHS and RHS of equation (7a) that reflect the marginal costs under a pure price-based regulation receive a higher weight if ω_U/ω_R $(= \frac{\partial \underline{\epsilon}}{\partial \lambda}/\underline{e} = \frac{\partial \overline{\epsilon}}{\partial \lambda}/\overline{e})$ is large. Intuitively, if price controls are not used, these terms (as well as the conditions in the expectation operators) drop out. Equation (7a) is then identical to the optimality condition under pure quantity control (equation (3)). With price bounds, the larger the change in the threshold levels induced by a change in the allocation factor, the higher is the weight on the marginal cost of introducing the respective bound. The weight becomes high if the uncertainty effect is lower than the reallocation effect; by definition this implies that the change in the MAC cost due to technology uncertainty counteract the change caused by the emission uncertainty. In turn, there has to be a larger change in the threshold level implying a larger shift in the marginal cost of adjusting the allocation factor.

Equations (7b) and (7c) characterize the trade-off in choosing the optimal price floor and ceiling, respectively. Changing a price control has two effects. First, reallocating abatement between sectors changes the MAC under the price regime change in both sectors (first term). The T sector's MAC are given by the respective price control and the weighting term ω_R evaluates the expected difference between the price bound and the realized marginal cost in the T sector. Second, a change in a price floor or ceiling causes a change in the threshold level. This is evaluated in the second term weighted with the marginal change of the threshold level (ω_U).

2.6. *Ex-ante optimal policies with abatement bounds*

We now turn to the situation in which the regulator imposes a lower ($\underline{a}$) and upper ($\overline{a}$) bound on the amount of abatement in the ETS sector. In this case, the objective function is similar as in the case with price bounds shown in (4).[17] Cutoff levels for ϵ_T and the allocation factor are again functions of policy

[16] As for a given choice of $\{\underline{P}, \overline{P}\}$, the threshold levels for ϵ are known, the marginal costs under price controls are known for sector T while they are uncertain for sector N. This explains the use of expectation operators for the second and third summands on the RHS of equation (7a).

[17] Equation (B.5) in Appendix D states the regulator's objective function for hybrid policies with abatement bounds.

choice variables with the difference that these now depend on abatement bounds rather than on price bounds, i.e. $\underline{\epsilon}\left(\lambda, \underline{a}\right)$, $\overline{\epsilon}\left(\lambda, \overline{a}\right)$, $\underline{\lambda}\left(\lambda, \underline{a}\right)$, and $\overline{\lambda}\left(\lambda, \overline{a}\right)$.

Under a hybrid policy with abatement bounds, the cutoff levels are implicitly defined by:[18]

$$\epsilon_T^0 + \underline{\epsilon}\left(\lambda, \underline{a}\right) - \lambda \overline{e} = \underline{a} \implies \underline{\epsilon}\left(\lambda, \underline{a}\right) \tag{8a}$$

$$\epsilon_T^0 + \underline{\epsilon} - \underline{\lambda}\left(\lambda, \underline{a}\right) \overline{e} = \underline{a} \implies \underline{\lambda}\left(\lambda, \underline{a}\right) . \tag{8b}$$

Taking partial derivatives of expressions for the cutoff levels for ϵ with respect to policy choice variables yields: $\partial \underline{\epsilon} / \partial \lambda = \partial \overline{\epsilon} / \partial \lambda = \overline{e}$ and $\partial \underline{\epsilon} / \partial \underline{a} = \partial \overline{\epsilon} / \partial \overline{a} = 1$. As baseline emissions uncertainty linearly affects abatement, a change in the allocation factor shifts the cutoff level by the same amount (taking into account that the allocation factor is defined as share of the total emission level). Similarly, a change in the abatement bound changes the threshold level by the exact same amount. Policy variables impact the the endogenous allocation factor as follows: $\partial \underline{\lambda} / \partial \lambda = \partial \overline{\lambda} / \partial \lambda = 0$ and $\partial \underline{\lambda} / \partial \underline{a} = \partial \overline{\lambda} / \partial \overline{a} = -\overline{e}^{-1}$. As in the price bound case, a change in the fulfillment factor does not affect the endogenous fulfillment factor as every change is balanced by the amount reallocated. Changing the abatement bound requires decreasing the allocation factor in order to hold the quantity balance.

Proposition 4. *A hybrid policy with abatement bounds fails to exploit information on firms' abatement technology when setting ex-ante minimum and maximum bounds on the permissible level of abatement.*

Proof. In contrast to equations (6b)–(6c), equations (8a) and (8b) do not contain any information on the change of the MAC function. □

While Proposition 4 summarizes a basic insight that is not very surprising—namely that policies aimed at targeting quantities rather than prices an ETS sector do not incorporate any information about the price and hence MACs of firms when determining abatement bounds—it bears out a strong implication and, in fact, foreshadows the main drawback of hybrid policies with abatement bounds when compared with policies with price bounds. Due to their ability to make use of information on firms' (marginal) abatement costs, hybrid policies with price bounds are better suited to cope with technology uncertainty. While a policy with abatement bounds is able to address baseline emissions uncertainty, it is not effective in dealing with risks that affect firms' abatement technology. In contrast, a hybrid policy with price bounds can hedge against both types of uncertainty.

The first-order conditions for the *ex-ante* optimal hybrid policy with abatement bounds can be written as:[19]

$$\lambda : \quad E\left[\frac{\partial C_T}{\partial a_T}\middle| \underline{\epsilon} \leq \epsilon_T \leq \overline{\epsilon}\right] + \frac{\partial C_T}{\partial a_T}\bigg|_{\underline{\epsilon}} + \frac{\partial C_T}{\partial a_T}\bigg|_{\overline{\epsilon}} = E\left[\frac{\partial C_N}{\partial a_N}\middle| \underline{\epsilon} \leq \epsilon_T \leq \overline{\epsilon}\right] + \mathbb{E}\left[\frac{\partial C_N}{\partial a_N}\middle| \underline{\epsilon} \leq \epsilon_T\right] + \mathbb{E}\left[\frac{\partial C_N}{\partial a_N}\middle| \overline{\epsilon} \geq \epsilon_T\right] \tag{9a}$$

[18] Analogous definitions for the upper cutoff levels apply and are omitted here for brevity.

[19] Appendix D contains the derivations.

$$\underline{a}: \quad \left[\frac{\partial C_T}{\partial a_T}\bigg|_{\underline{a}} \bigg| \epsilon_T \leq \underline{\epsilon} \right] + \frac{\partial C_T}{\partial a_T}\bigg|_{\underline{\epsilon}} = \mathbb{E}\left[\frac{\partial C_N}{\partial a_N} \bigg| \underline{\epsilon} \leq \epsilon_T \right] + \mathbb{E}\left[\frac{\partial C_N}{\partial a_N} \bigg| \underline{\epsilon} = \epsilon_T \right] \tag{9b}$$

$$\overline{a}: \quad \left[\frac{\partial C_T}{\partial a_T}\bigg|_{\overline{a}} \bigg| \epsilon_T \geq \overline{\epsilon} \right] + \frac{\partial C_T}{\partial a_T}\bigg|_{\overline{\epsilon}} = \mathbb{E}\left[\frac{\partial C_N}{\partial a_N} \bigg| \overline{\epsilon} \geq \epsilon_T \right] + \mathbb{E}\left[\frac{\partial C_N}{\partial a_N} \bigg| \overline{\epsilon} = \epsilon_T \right]. \tag{9c}$$

The interpretation of FOCs is similar to the case of a policy with price bounds trading off the expected difference in sectoral MACs with the sum of sectoral cost changes created by introducing abatement bounds. A key difference as compared to policies with price bounds is, however, that as abatement bounds are not capable to infer information on the abatement cost functions and, consequently, do not include expected changes in the slopes of the MAC curves; all terms transporting information on firms' abatement technology are missing.

3. Quantitative framework for empirical analysis

We complement our theoretical analysis of hybrid policies under partitioned environmental regulation with an empirical analysis of EU climate policy investigating the question to what extent introducing hybrid policies in the EU ETS could lower the costs of reaching EU's emissions reductions goals. To this end, we develop and apply a stochastic policy optimization model with equilibrium constraints for the European carbon market that is calibrated to empirically derived MAC curves.

This section describes how we operationalize the theoretical framework presented in the previous section by (1) deriving MAC curves from a large-scale general equilibrium model of the European economy, (2) sampling MAC curves and baseline emissions for representative firms the ETS and non-ETS sectors to reflect different types of uncertainty in an empirically meaningful way, and (3) detailing our computational strategy to solve for optimal hybrid policies.

3.1. Derivation of marginal abatement cost functions

Following established practice in the literature (see, for example, Klepper & Peterson, 2006; Böhringer & Rosendahl, 2009; Böhringer et al., 2014), we derive MAC curves from a multi-sector numerical general equilibrium (GE) model of the European economy. The model structure and assumptions follow closely the GE model used in Böhringer et al. (2016).

The advantage of deriving MAC curves from a GE model is that firms' abatement cost functions are based on firms' equilibrium responses to a carbon price, thus reflecting both abatement through changing the input mix and the level of output while also taking into account endogenously determined price changes on output, factor, and intermediate input markets. By incorporating market responses on multiple layers, the derived MAC curves go beyond a pure technology-based description of firms' abatement possibilities. The sectoral resolution further enables us to adequately represent the sectoral boundaries of the partitioned regulation to separately identify the MACs of sectors inside and outside of the EU ETS.

3.1.1. Overview of general equilibrium model used to derive MAC curves

We briefly highlight the key features of the numerical GE model here. Appendix C contains more detail along with a full algebraic description of the model's equilibrium conditions. The model incorporates rich detail in energy use and carbon emissions related to the combustion of fossil fuels. The energy goods identified in the model include coal, gas, crude oil, refined oil products, and electricity. In addition, the model features energy-intensive sectors which are potentially most affected by carbon regulation, and other sectors (services, transportation, manufacturing, agriculture). It aggregates the EU member states into one single region.

In each region, consumption and savings result from the decisions of a continuum of identical households maximizing utility subject to a budget constraint requiring that full consumption equals income. Households in each region receive income from two primary factors of production, capital and labor, which are supplied inelastically. Both factors of production are treated as perfectly mobile between sectors within a region, but not mobile between regions. All industries are characterized by constant returns to scale and are traded in perfectly competitive markets. Consumer preferences and production technologies are represented by nested constant-elasticity-of-substitution (CES) functions. Bilateral international trade by commodity is represented following the Armington (1969) approach where like goods produced at different locations (i.e., domestically or abroad) are treated as imperfect substitutes. Investment demand and the foreign account balance are assumed to be fixed.

A single government entity in each region approximates government activities at all levels. The government collects revenues from income and commodity taxation and international trade taxes. Public revenues are used to finance government consumption and (lump-sum) transfers to households. Aggregate government consumption combines commodities in fixed proportions.

The numerical GE model makes use of a comprehensive energy-economy dataset that features a consistent representation of energy markets in physical units as well as detailed accounts of regional production and bilateral trade. Social accounting matrices in our hybrid dataset are based on data from the Global Trade Analysis Project (GTAP) (Narayanan et al., 2012). The GTAP dataset provides consistent global accounts of production, consumption, and bilateral trade as well as consistent accounts of physical energy flows and energy prices.

We use the integrated economy-energy dataset to calibrate the value share and level parameters using the standard approach described in Rutherford (1998). Response parameters in the functional forms which describe production technologies and consumer preferences are determined by exogenous parameters. Table C.2 in the Appendix C lists the substitution elasticities and assumed parameter values in the model. Household elasticities are adopted from Paltsev et al. (2005b) and Armington trade elasticity estimates for the domestic to international trade-off are taken from GTAP as estimated in Hertel et al. (2007). The remaining elasticities are own estimates consistent with the relevant literature.

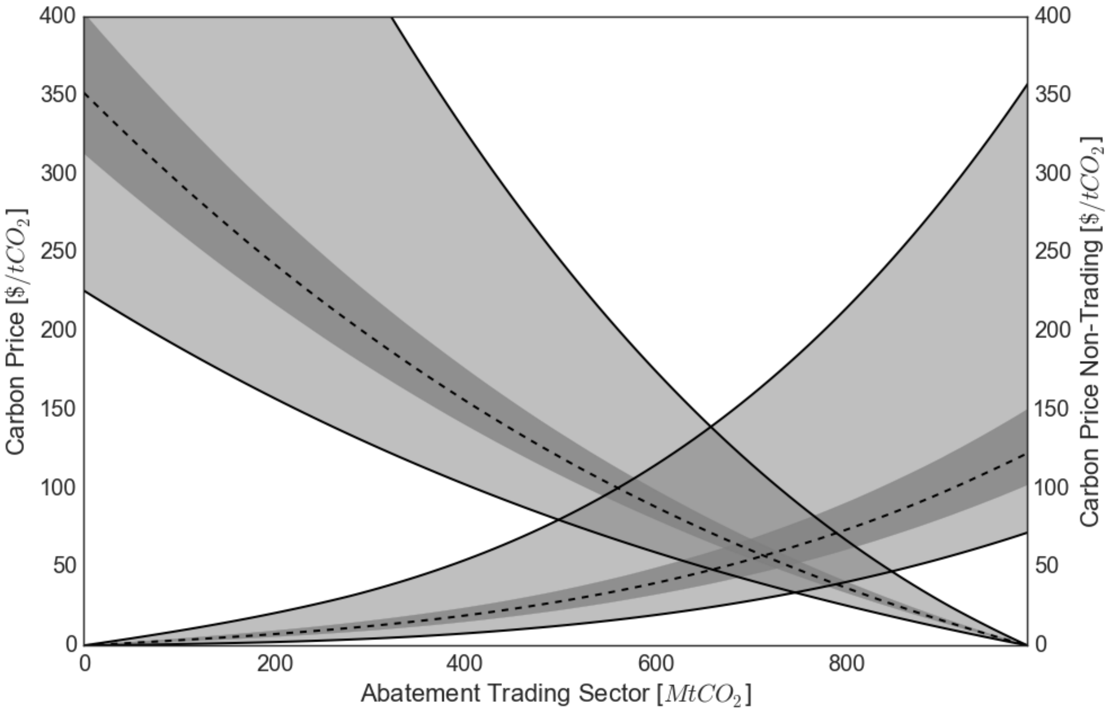
3.2. Sources of uncertainty and sampling of marginal abatement cost curves

To empirically characterize uncertainty in firms' abatement technology and baseline emissions, we adopt the following procedure for sampling MAC curves for the ETS and non-ETS sector.

3.2.1. Uncertainty in firms' technology

Firms' abatement costs depend on their production technology. For each sector (or representative firm in a sector), production functions are calibrated based on historically observed quantities of output and inputs (capital, labor, intermediates including carbon-intensive inputs). To globally characterize CES technologies, information on elasticity of substitution (EOS) parameters are needed to specify second- and higher

Figure 2: Distribution of sampled MAC curves for technology uncertainty



Note: The MAC curve of the ETS sector runs from left to right; the one for the non-ETS from right to left. Dotted lines and dark shaded areas refer, respectively, to the mean and the interquartile range.

order properties of the technology. Given a calibration point, EOS parameters determine MAC curves. Unfortunately, there do not exist useful estimates for EOS parameters in the literature that would characterize uncertainties involved. We assume that EOS parameters for each sector are uniformly and independently distributed with a lower and upper support of, respectively, 0 and 1.5 times the central case value which we take from the literature (Narayanan et al., 2012). We then create a distribution of 10'000 MAC curves by using least squares to fit a cubic function to the price-quantity pairs sampled from 10'000 runs of the numerical GE model. Each run is based on a random draw of all EOS parameters from their respective distribution. For each draw, we impose a series of carbon taxes from zero to 150 $\$/tCO_2$.[20] Following the design of the EU ETS, we consider electricity, refined oils, and energy intensive industries to be part of the trading system. All remaining sectors, including final household consumption, are subsumed under the non-trading sector. We carry out this procedure for each partition independently thereby assuming that technology shocks across sectors are uncorrelated.

Figure 2 shows the resulting distribution of MAC curves for the ETS and non-ETS sector. It is apparent that the variation in the MAC estimates increases with the level of abatement. The MAC curves of the ETS sector tend on average to be less steep implying that firms' in the ETS sectors bear a larger part of the abatement burden.[21]

[20]We assume that the carbon revenue, net of what has to be retained to hold government spending constant in real terms, is recycled to households in a lump-sum fashion.

[21]This is also driven by including the transport sector and final household consumption sector into the non-ETS sector. As the European transport sector is subject to high fuel taxes, this causes large and costly tax interaction effects (Paltsev et al., 2005a;

3.2.2. Baseline emissions uncertainty

The distribution of baseline emissions for each sector is derived by applying the shock terms for the ETS and non-ETS sector on the respective "certain" baseline emissions (e_i^0) as given by the numerical GE model. For our quantitative application, we have in mind the European economy around the year 2030. Assuming that baseline emissions grow with a maximum rate of ≈1% per year between 2015 and 2030, this would suggest about 15% higher emissions relative to e_i^0.[22] At the same time we want to allow for the possibility of reduced baseline emissions while discarding unrealistically large reductions. Therefore, we assume that shocks in both sectors follow a joint truncated normal distribution with mean zero and a standard deviation of 5%. Lower and upper bounds for the truncation are set equal to ±15% of the baseline emissions. Shocks on sectoral baseline emissions are meant to capture both common GDP shocks, that equally affect both sectors, as well as sector-specific shocks. We thus consider alternative assumptions about the correlation between sectoral baseline emissions shocks; we consider three cases in which the correlation coefficient is $\rho = 0$, $\rho = -0.5$, and $\rho = +0.5$, respectively. Truncated normal distributions are sampled using 100'000 draws using rejection sampling (Robert & Casella, 2004).

3.2.3. Combining uncertainties and scenario reduction

The two types of uncertainty are assumed to be independent, i.e. we assume that technology uncertainty is not affected by the baseline emissions uncertainty. We can thus combine the two types of uncertainty by simply adding each technology shock to any baseline emissions shock and vice versa. The size of the combined sample comprises $1e^5 \times 1e^4 = 1e^9$ observations.

To reduce computational complexity, we employ scenario reduction techniques to approximate the distributions. Distributions for technology and baseline emissions uncertainty are approximated each using 100 points which reduces the total number of scenarios to 10'000. Approximation is done using k-means clustering (Hartigan & Wong, 1979) under a Euclidean distance measure and calculating centroids as means of the respective cluster. For the technology distributions, we cluster on the linear coefficient of the MAC curve and derive the mean of the higher order coefficients of the cubic MAC function afterwards. The original and reduced distributions, along with histograms and kernel density estimates of the respective marginal distributions, are shown in Figures D.7 and D.8 in Appendix D.

3.3. Computational Strategy

States of the world (SOW), indexed by s, are represented by MAC curves for the ETS and non-ETS sectors, C_{is}, reflecting uncertainty both in firms' abatement technology and baseline emissions. Let π_s denote the probability for the occurrence of state s. Under all policies, the regulator minimizes expected total abatement costs

$$\sum_s \pi_s C_{is} \left(\tilde{e}_{is}^0 - e_{is} \right) \tag{10}$$

subject to an economy-wide emissions target $\overline{e}$. $\tilde{e}_{is}^0 \geq 0$ and $e_{is} \geq 0$ denote the level of emissions under "no intervention" and with policy, respectively.

Abrell, 2010). Furthermore, we exclude non-CO_2 greenhouse gases from our analysis, in particular methane emissions from agriculture, which offer sizeable abatement potential and relatively low cost (Hyman et al., 2002).

[22] Absent any changes in energy efficiency and structural change, this would correspond to an annual average growth rate of European GDP of the same magnitude.

3.3.1. Policies with pure quantity control

The computation of first-best and second-best policies with pure quantity control is straightforward as it involves solving standard non-linear optimization problems. Under a first-best policy, the regulator can condition instruments on SOWs thereby effectively choosing e_{is}. We can compute first-best policies by minimizing (10) subject to the following constraints

$$\overline{e} \geq \sum_i e_{is} \quad (P_s) \quad \forall s \tag{11}$$

which ensure that the environmental target $\overline{e}$ is always met. P_s is the dual variable on this constraint and can be interpreted as the (uniform) optimal first-best emissions permit price.

Under the second-best policy with pure quantity control, the regulator decides *ex ante* on the split of the economy-wide target between sectors, i.e. they choose sectoral targets $\overline{e}_i \geq 0$ independent from s. We compute second-best policies with pure quantity control by minimizing (10) subject to following constraints:

$$\overline{e} \geq \sum_i \overline{e}_i \quad (P) \tag{12a}$$

$$\overline{e}_i \geq e_{is} \quad (P_{is}) \quad \forall i, s\,. \tag{12b}$$

(12a) ensures that the economy-wide target is met; the associated dual variable P is the expected permit price. (12b) ensures that emissions in each SOW are equal to the respective ex-ante chosen sectoral target. The associated dual variables are the *ex-post* carbon prices for each sector.

3.3.2. Hybrid policies with price and abatement bounds

The problem of computing ex-ante optimal hybrid policies with bounds on either price or abatement falls outside the class of standard non-linear programming. The issue is that a priori it is unknown in what SOW the bounds will be binding. Cutoff levels, which define SOW in which bounds are binding, are endogenous functions of the policy choice variables. Hence, the integral bounds in the regulator's objective function (4) are endogenous and cannot be known beforehand. We thus need to specify an endogenous "rationing" mechanism that re-allocates emissions targets between sectors whenever one of the bounds becomes binding.

To this end, we use a complementarity-based formulation which explicitly represents "rationing" variables for lower and upper bounds denoted $\underline{\mu}_s$ and $\overline{\mu}_s$, respectively. They appear in the following constraints which ensure that ex-post emissions in each sector are aligned with the ex-ante emissions allocation:

$$\overline{e}_i + 1_T(i)\left(\overline{\mu}_s - \underline{\mu}_s\right) \geq e_{is} \quad \perp \quad P_{is} \geq 0 \quad \forall i, s \tag{13}$$

where $1_T(i)$ is an indicator variable which is equal to one if $i = T$ and -1 otherwise.[23] Condition (13) is similar to (12b) in the pure quantity control case. The formulation as complementarity constraints is necessary here as it enables explicitly representing constraint on dual variables (P_{is}). This allows us to formulate policies in terms of dual variables which is needed to a representation of the hybrid policies investigated here.

[23] We use the perpendicular sign $\perp$ to denote complementarity, i.e., given a function $F\colon \mathbb{R}^n \longrightarrow \mathbb{R}^n$, 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, $F(z) \geq 0 \perp z \geq 0$.

For the case of policies with price bounds, "rationing" variables $\underline{\mu}_s$ and $\overline{\mu}_s$ are determined by the following constraints:

$$P_{Ts} \geq \underline{P} \quad \perp \quad \underline{\mu}_s \geq 0 \quad \forall s \tag{14a}$$

$$\overline{P} \geq P_{Ts} \quad \perp \quad \overline{\mu}_s \geq 0 \quad \forall s\,. \tag{14b}$$

As long as the price is strictly larger than the price floor, $\overline{\mu}_s = 0$. If the price floor becomes binding, complementarity requires that $\underline{\mu}_s > 0$. In this case, the emissions budget in the T (N) sector decreases (increases), in turn increasing the price in the T sector.

For the case of abatement bounds, $\underline{\mu}_s$ and $\overline{\mu}_s$ are determined by the following constraints:

$$\overline{e}^0_{Ts} - e_{Ts} \geq \underline{a} \quad \perp \quad \underline{\mu}_s \geq 0 \quad \forall s \tag{15a}$$

$$\overline{a} \geq \overline{e}^0_{Ts} - E_{Ts} \quad \perp \quad \overline{\mu}_s \geq 0 \quad \forall s\,. \tag{15b}$$

The problem of optimal policy design can now be formulated as a *Mathematical Program with Equilibrium Constraints* (MPEC) minimizing expected abatement cost (10) subject to the emission constraints (12a), (13), and (14a) and (14b) for the case of price bounds or (15a) and (15b) for the case of abatement bounds.

As MPECs are generally difficult to solve due to the lack of robust solvers (Luo et al., 1996), we reformulate the MPEC problem as a mixed complementarity problem (MCP) (Mathiesen, 1985; Rutherford, 1995) for which standard solvers exists.[24] The MCP problem comprises complementarity conditions (13), (14a) and (14b) (for the case of price bounds), (15a) and (15b) (for the case of abatement bounds), and an additional condition,

$$C'_{is}\left(\overline{e}^0_{is} - e_{is}\right) \geq P_{is} \quad \perp \quad e_{is} \geq 0 \quad \forall\, i, s \tag{16}$$

which determines firms' cost-minimizing level of abatement in equilibrium. To find policies that minimize (10), we perform a grid search over policy choice variables $\overline{e}_i$ and $(\underline{P}, \overline{P})$ or $(\underline{a}, \overline{a})$, and compare total costs.[25]

4. Simulation results

4.1. Policy context and assumptions underlying the simulation dynamics

Our quantitative analysis seeks to approximate current EU Climate Policy. Under the "2030 Climate & Energy Framework" proposed by the European Commission (EC, 2013), it is envisaged that total EU GHG emissions are cut by at least 40% in 2030 (relative to 1990 levels). As there is still considerable uncertainty regarding the precise commitment, and given that we do not model non-CO_2 GHG emissions, we assume for our analysis a 30% emissions reduction target which is formulated relative to the expected value of baseline emissions.[26]

The "Effort Sharing Decision" under the "'2030 Climate & Energy Package" (EC, 2008) defines reduction targets for the non-ETS sectors. We use this information together with historical emissions data from the European Environment Agency to calculate an allocation factor of $\hat{\lambda} = .41$ which determines the sectoral emissions targets under current EU climate policy.

[24] We use the *General Algebraic Modeling System* (GAMS) software and the PATH solver (Dirkse & Ferris, 1995) to solve the MCP problem. We use the CONOPT solve (Drud, 1985) to solve the NLP problems when computing first-best and second-best pure quantity control policies.

[25] We have used different starting values, ranges, and resolutions for the grid search to check for local optima. We find that total costs exhibit an U-shaped behavior over the policy instrument space which indicates the existence of a global cost minimum.

[26] Since we assume $\mathbb{E}(\epsilon_i) = 0$, $\mathbb{E}\left(e^0_i + \epsilon_i\right) = e^0_i$.

Table 1: Comparison of expected abatement costs, allocation factor and bounds for alternative policy designs under first-, second-, and third-best policy environments[a]

	First-best policy	Second-best policies			Third-best policies		
	λ^*	λ^*	$\lambda^*, \underline{P}, \overline{P}$	$\lambda^*, \underline{a}, \overline{a}$	$\hat{\lambda}$	$\hat{\lambda}, \underline{P}, \overline{P}$	$\hat{\lambda}, \underline{a}, \overline{a}$
Expected cost (bill. $/per year)							
Total	39.3	41.9	40.5	40.6	52.8	40.8	40.7
ETS	24.2	25.4	24.3	24.7	11.8	24.1	24.3
Non-ETS	15.1	16.6	16.1	15.8	41.0	16.6	16.3
Ex-ante allocation factor λ							
	optimal	.34	.34	.33	.41	.41	.41
Carbon permit price ($/ton CO_2) in ETS							
min	37	21	77*	51	8	86*	54
max	197	278	101*	168	174	124*	165
Abatement (mill. ton CO_2) in ETS							
min	570	572	583	822**	372	617	839**
max	1'138	1'073	1'058	859**	874	997	853**
Probability that [lower,upper] price or abatement bound in ETS binds							
	–	–	[0.43,0.27]	[0.35,0.5]	–	[0.95,0]	[0.98,0]
Expected carbon price ($/ton CO_2) and stdev (in parentheses)							
ETS	86 (18)	89 (31)	87 (10)	88 (21)	50 (19)	86 (4)	87 (20)
Non-ETS	86 (18)	89 (37)	88 (37)	87 (32)	156 (51)	88 (41)	89 (34)

Notes: $\hat{\lambda}$ denotes the "third-best" exogenous allocation factor reflecting the share of the ETS emissions budgets in total emissions based on current EU climate policy (EC, 2008).
[a]Results shown assume negative correlation of baseline emissions shocks between sectors ($\rho = -0.5$).
*Indicates ex-ante optimal floor and ceiling on ETS permit price.
**Indicates ex-ante optimal lower and upper bounds on abatement in ETS sector.

4.2. *Ex-ante assessment of alternative hybrid policy designs*

We start by examining the ex-ante effects of hybrid policies with price and abatement bounds under partitioned environmental regulation relative to pure quantity-based regulation. We analyze hybrid policies in the context of first-, second-, and third-best regulation. A first-best policy enables choosing a state-contingent allocation factor whereas under a second-best policies an allocation factor has to be chosen ex-ante; in a third-best policy the allocation factor is exogenously given and cannot be set. We first focus on the impacts in terms of expected costs which represent the regulator's objective. We then provide insights into how alternative hybrid policies perform under different assumptions about the type and structure of uncertainty. Finally, we analyze the potential of hybrid policies to lower expected costs in alternative third-best settings.

4.2.1. *Impacts on expected costs*

Table 1 presents a comparison of alternative policy designs under first-, second-, and third-best policy environments in terms of expected abatement costs, policy choice variables, and expected carbon prices.

Under a first-best policy which can condition the allocation factor λ (or the uniform carbon price) on states of the world, the expected total abatement costs of reducing European economy-wide CO_2 emissions by 30% are 39.3 bill.$ with an expected carbon price of 86$/ton. 61% of the total expected costs are borne by the ETS sector. Uncertainty increases the expected costs of regulation in second- or third-best best policy environments relative to a first-best policy: if an ex-ante optimal λ can be chosen, costs increase by 2.6 bill.$ or by about 7%; a third-best policy in which λ is exogenously given increases costs by 13.5 bill.$ or by about one third. Importantly, second- and third-best policies using a pure quantity-based approach based on λ, bring about a significantly larger variation in sectoral carbon prices as is evidenced by both lower minimum and higher maximum ETS permit prices as well as larger standard deviations in expected carbon prices in the ETS and non-ETS sectors.

The expected excess costs of environmental regulation relative to a first-best policy are significantly reduced with hybrid policies. Under a second-best world, introducing ex-ante optimal price bounds in the ETS reduces the expected excess total abatement costs to 1.1 bill.$ which corresponds to a reduction of 56% (= $(1.1/2.6 - 1) \times 100$) in expected excess costs relative to a first-best policy. In the third-best world, the cost reduction is particularly large. Here, a ex-ante optimal policy with price bounds reduces expected excess costs to 1.4 bill.$ which equals a 89% (= $(1.4/13.5 - 1) \times 100$) reduction in expected excess costs relative to first-best regulation. The effects of a hybrid policies with abatement bounds on expected costs are of similar magnitudes.

The reason why second-best hybrid policies bring about sizeable reductions in expected costs of environmental regulation relative to pure quantity-based regulatory approaches is that they work as a mechanism to prevent too large differences in MACs between the ETS and non-ETS sectors. This can be seen by noting that the minimum and maximum carbon prices in the ETS sector under hybrid policies in both second- and third-best cases describe a more narrow range around the optimal first-best expected carbon price of 86. In addition, the standard deviation of the expected carbon price in the ETS sector decreases substantially.

In the third-best, the effectiveness of hybrid policies rests on an additional effect which stems from correcting the non-optimal allocation factor. A third-best allocation factor of $\hat{\lambda} = 0.41$ compared to the second-best allocation factor $\lambda^* = 0.34$ means that there is too little abatement in the ETS sector (or, equivalently, an over-allocation of the emissions budget). By establishing a lower bound for the ETS price or the level of abatement in the ETS sector, hybrid polices effectively shift abatement from the non-ETS to the ETS sector. The lower price bound, set at 86$/ton, binds with a probability of 0.95; the lower bound on abatement binds with a similarly high probability of 0.98. As the motive to correct the non-optimal emissions split under EU climate policy is particularly strong under the third-best case, hybrid policies work here effectively as a carbon tax.

Finally, the expected costs under a third-best with price or abatement bounds are relatively close to a second-best pure quantity control policy (expected costs are only slightly lower under the second-best policy with about 1 bill.$). This result bears out an important policy implication: if it is politically infeasible to correct policy decisions which have been taken in the past, manifested here through an exogenously given allocation factor, adding price or abatement bounds to the existing policy can achieve policy outcomes that are close to the optimum which could have been achieved under previous policy.

4.2.2. *Impacts under different assumptions about uncertainty*

In the absence of any uncertainty, there is no distinction between price and quantity controls, and hence no case for hybrid policies which combine elements of price and quantity control. To further investigate the performance of hybrid policies, we thus examine cases in which we switch off either type of uncertainty (i.e. baseline emissions or abatement technology uncertainty). In addition, we analyze how the assumed correlation structure between sectoral baseline emissions shocks (ρ) affects results. Table 2 summarizes the performance of hybrid policies relative to a pure quantity control approach in terms of impacts on expected

Table 2: Percentage reduction in expected excess abatement costs of hybrid policies relative to pure quantity-based regulation for alternative assumptions about uncertainty[a]

	Second-best policies				Third-best policies			
	$(\lambda^*, \underline{P}, \overline{P})$		$(\lambda^*, \underline{a}, \overline{a})$		$(\hat{\lambda}, \underline{P}, \overline{P})$		$(\hat{\lambda}, \underline{a}, \overline{a})$	
	Correlation in sectoral baseline emissions shocks							
	$\rho = -0.5$	$\rho = 0.5$	$\rho = -0.5$	$\rho = 0.5$	$\rho = -0.5$	$\rho = 0.5$	$\rho = -0.5$	$\rho = 0.5$
Baseline emissions + technology uncertainty	56.4	10.2	50.3	0.2	89.3	76.1	89.8	75.1
Only baseline emissions uncertainty	63.4	0.4	63.4	0.4	93.6	78.9	93.6	78.7
Only abatement technology uncertainty	55.4	55.5	0	0	93.7	93.7	95.2	95.2

Notes: [a]Expected *excess* abatement costs are defined as the difference in expected costs relative to the first-best policy. Numbers above refer to percentage reductions in expected excess costs of a hybrid policy relative to the respective pure quantity control policy.

excess abatement costs[27] for these alternative assumptions about uncertainty. Expected *excess* abatement costs are defined as the difference in expected costs relative to the first-best policy. Several insights emerge.

First, abatement bounds are completely ineffective when only technology uncertainty is present, reflecting the insight from Proposition 4. As ex-ante abatement bounds do not make use of firm's marginal abatement costs, and hence information on firms' technology, they cannot bring about reductions in *expected* excess abatement costs under a second-best case. It is important to understand that this result only holds in the second best in which it is possible to choose an ex-ante optimal λ, in turn implying that there is no scope for abatement bounds to reduce expected costs from correcting λ. Under a third-best case, abatement bounds do indeed reduce expected costs—even if only baseline emission uncertainty is present—but this is due to correcting $\hat{\lambda}$ and not due to addressing baseline emissions uncertainty per se. In contrast, a hybrid policy with price bounds brings about substantial cost reductions under both types of uncertainties under a second best case. If only baseline emissions uncertainty is present, price bounds, however, yield an reduction in expected excess costs relative to abatement bounds because they loose their comparative advantage due to being able to address technology uncertainty.

Second, under third-best policies, price and abatement bounds yield virtually identical outcomes. The reason is simply that given a non-optimal third-best allocation factor $\hat{\lambda}$, both types of bounds primarily work to correct $\hat{\lambda}$. Table 2 suggests that this brings about larger reductions in expected excess abatement costs than hedging against either type of uncertainty too prevent differences in sectoral MACs.

Third, reductions in expected excess abatement costs are the smaller, the larger is the correlation between baseline emissions shocks. The more positively sectoral baseline emissions shocks are correlated, the more likely are cases in which a higher abatement is needed in both sectors. Given the relative slopes of sampled MAC curves in Figure 2, this tends to decrease the difference between sectoral MACs. Again, this effect is particularly visible under second-best policies whereas for third-best cases it is strongly confounded by cost reductions emanating from correcting $\hat{\lambda}$.

Differences in the ability of alternative hybrid policies to reduce expected abatement costs when both types of uncertainty are present can now be understood by combining cases which isolated the impact

[27]See the note below Table 2 for the definition of expected excess costs

Table 3: Percentage reduction in expected excess abatement costs of third-best optimal hybrid policies relative to pure quantity-based regulation for different third-best allocation factors ($\hat{\lambda}$)

	Third-best allocation factor ($\hat{\lambda}$)							
	0.10	0.20	0.30	0.34[a]	0.40	0.45	0.50	0.60
Hybrid policy with price bounds								
$\rho = -0.5$	88.5	88.5	90.2	91.5	89.6	88.6	88.5	88.5
$\rho = +0.5$	74.1	74.1	81.7	88.8	77.3	74.2	74.0	74.0
Hybrid policy with abatement bounds								
$\rho = -0.5$	89.8	89.8	90.1	90.3	89.9	89.8	89.8	89.8
$\rho = +0.5$	75.4	75.4	78.6	87.4	75.6	75.0	75.0	75.0

Notes: Numbers for $\hat{\lambda} > 0.6$ are identical to the case $\hat{\lambda} = 0.6$ and are hence not shown. [a]Denotes the ex-ante optimal allocation factor.

of different types of uncertainties. In summary, hybrid policies with price bounds emerge as the ex-ante superior policy design when compared to abatement bounds, although both approaches yield very similar ex-ante outcomes under a third-best policy environment.

4.2.3. Alternative third-best cases

To what extent can expected abatement costs be reduced if an existing quantity-based control policy, as represented by a given $\hat{\lambda}$, is enhanced by introducing price or abatement bounds? The answer obviously depends on the nature of the third-best policy, i.e. the initially given $\hat{\lambda}$.

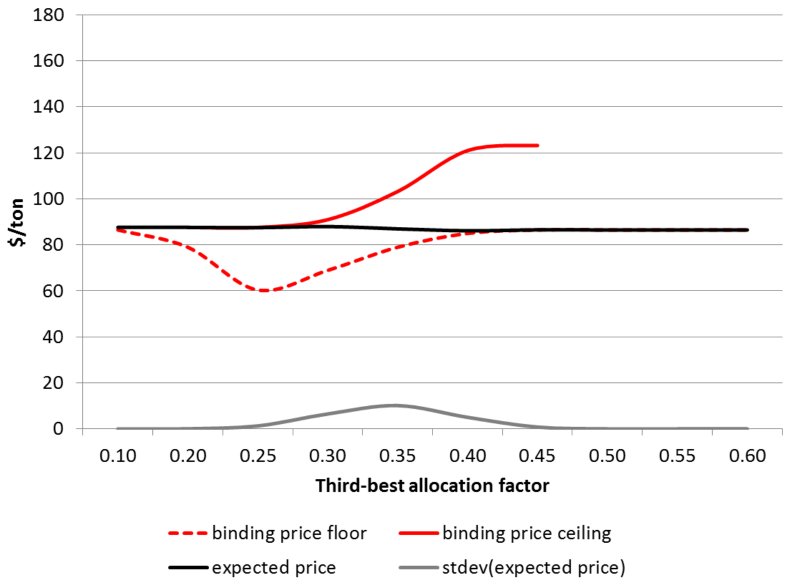
Table 3 displays reductions in expected abatement costs under alternative third-best policies. Irrespective of $\hat{\lambda}$, hybrid policies provide sizeable cost reductions on the order of 74% to 91%. Cost reductions in all cases peak at the second-best optimal allocation factor ($\lambda = 0.34$). Intuitively, the closer $\hat{\lambda}$ is to its optimal second-best value, the weaker is the motive to correct λ. This implies that price or abatement bounds can be used to a larger extent to address uncertainty, hence creating larger reductions in expected abatement costs.

Figure 3 provides further insight by taking a closer look at the ETS carbon price under a hybrid policy with price bounds (Panel (a)) and abatement bounds (Panel (b)) for different $\hat{\lambda}$. The major insight born out by Panel (a) is that a policy with price bounds effectively behaves as a pure price instrument, i.e. a carbon tax, if the deviation from $\hat{\lambda}$ with respect to the second-best optimal λ is sufficiently large. If $\hat{\lambda}$ is very small, the emissions budget (or amount of carbon permits) allocated to the ETS sector is small and the permit price tends to be high. Too high permit prices would imply too much abatement in the ETS sector, hence it is optimal for a hybrid policy with price bounds to impose a price ceiling. For $\hat{\lambda} \leq 0.25$, the price ceiling is equal to the expected carbon price with a standard deviation of virtually zero. This means that effectively a tax solution is chosen, i.e. the probability that the price ceiling binds converges to 1.

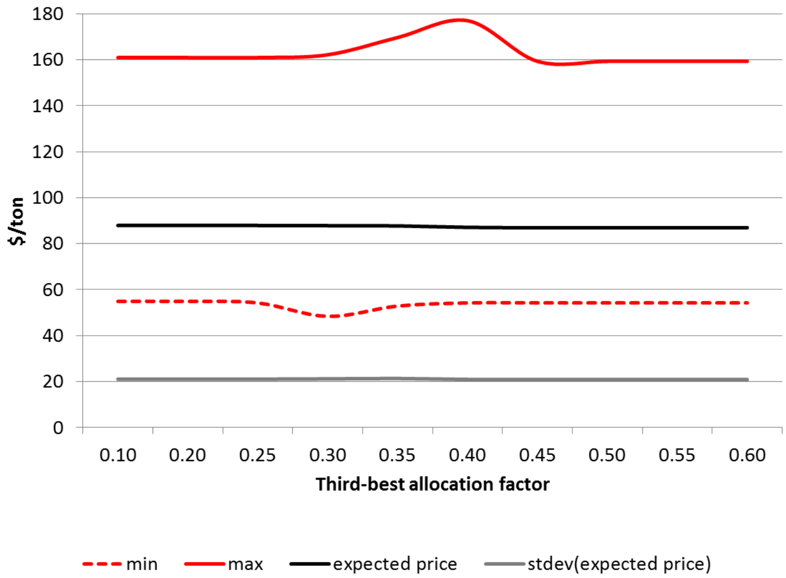
Similarly, for $\hat{\lambda} \geq 0.45$, the hybrid policy with price bounds resembles a pure tax policy now with the price floor determining the level of the tax in virtually 100% of the cases. A sufficiently larger $\hat{\lambda}$ means an oversupply of emissions permits to the ETS sector and hence too low prices which are counteracted by an always binding price floor (i.e. the price floor equals the expected carbon price which exhibits a standard deviation of zero). As $\hat{\lambda}$ approaches its second-best optimum, the need to correct the allocation factor becomes smaller. To address uncertainty, the lower and upper optimal price bounds in this case then allow for a positive range around the expected ETS permit price.

Panel (b) of Figure 3 shows that a policy with abatement bounds leads to a larger dispersion of the expected ETS permit price when compared to a policy with price bounds (while resulting in the same

Figure 3: ETS carbon price impacts of third-best optimal hybrid policies as function of third-best allocation factor ($\hat{\lambda}$)



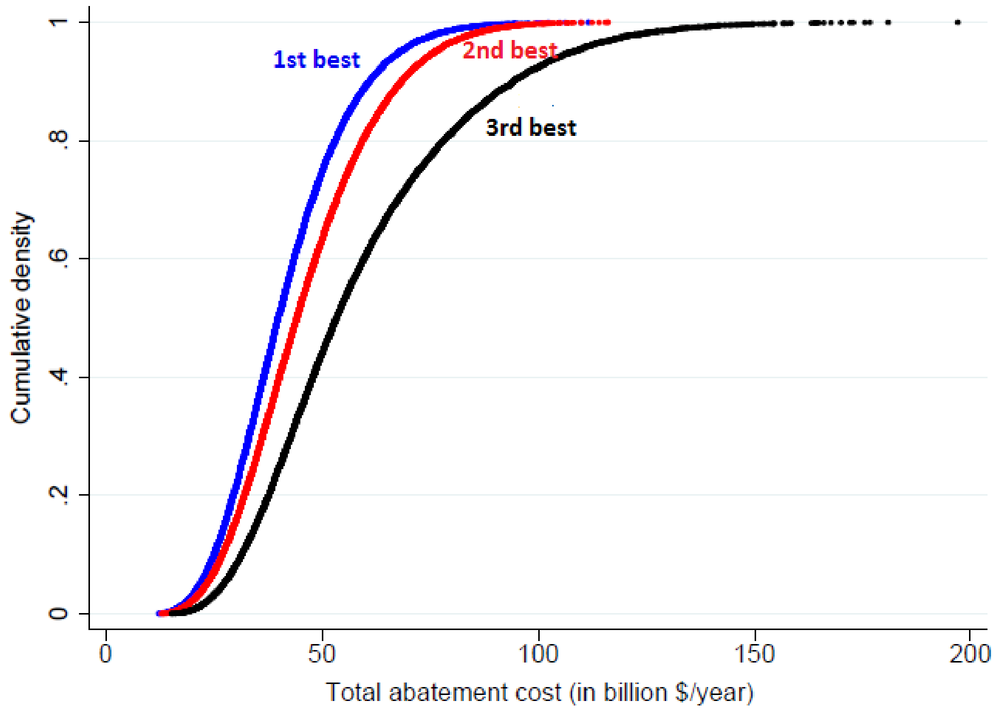
(a) Hybrid policy with price bounds



(b) Hybrid policy with abatement bounds

Note: Cases shown above assume negative correlation between ETS and non-ETS baseline emissions shocks ($\rho = -0.5$).

Figure 4: Cumulative distribution function for ex-post abatement costs under pure quantity-based regulation



Notes: Assumes $\hat{\lambda} = 0.41$ based on current EU climate policy). Cases shown assume a negative ($\rho = -0.5$) correlation in sectoral baseline emissions shocks. The respective distributions for $\rho = +0.5$ are similar and hence not shown here.

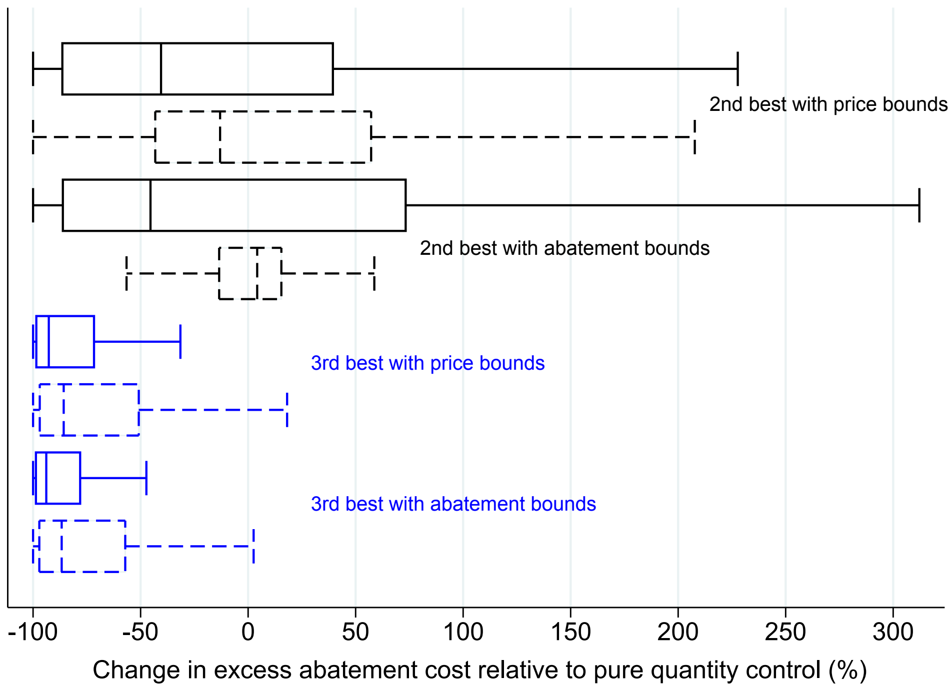
expected ETS permit prices). This result is not surprising given the previous discussion about the inability of abatement bounds to incorporate information about firms' abatement technology. Despite this shortcoming of abatement bounds, Table 3 shows that for the range of possible third-best cases, abatement bounds bring about relative similar reductions in expected abatement costs. This result again reflects that under third-best cases costs reduction are primarily achieved by correcting $\hat{\lambda}$, and less so by addressing directly uncertainty. Nevertheless, small differences exist between both types of hybrid policies. As abatement bounds target directly abatement, they provide a more direct way to correct $\hat{\lambda}$. They therefore perform slightly better than a policy with price bounds when the deviation of $\hat{\lambda}$ from its second-best optimum is sufficiently large. When $\hat{\lambda}$ is closer to its second-best optimum, price bounds are slightly better from an ex-ante perspective due to their ability to address technology uncertainty.

4.3. Impacts on ex-post abatement costs

So far, our empirical analysis has documented that hybrid policies with price or abatement bounds have the potential to reduce expected abatement costs for achieving a given environmental target when the regulation is partitioned. While the focus on expected cost is important as it arguably reflects a key criterion in policy decisions, it is at least as important for policymakers to have insights into the question how likely it is that hybrid policies can reduce *ex-post* abatement costs.

Figure 4 displays the cumulative distribution of *ex-post* abatement costs (in billion $/year) for a pure quantity-based regulatory approach under first-, second-, and third-best policy conditions. Given the uncertainty embedded in our sample of empirical MAC curves, it is evident that there is a substantial variation

Figure 5: Ex-post excess abatement costs of hybrid polices relative to pure quantity-based environmental regulation



Notes: Solid and dashed lines refer to cases assuming negative ($\rho = -0.5$) and positive ($\rho = +0.5$) correlation in sectoral baseline emissions shocks, respectively. Boxes show inter-quartile range and median. Whiskers show minimum and maximum outside values. Third-best policies assume $\hat{\lambda} = 0.41$ (based on current EU climate policy).

in ex-post cost outcomes. Ruling out the possibility of state-contingent hybrid policies, a hybrid policy can never be better than a first-best policy. The question, however, is how "close" the *ex-post* abatement cost distribution implied by hybrid policies—under both second- and third-best worlds—can be relative to first-best solution. In particular, can hybrid policies reduce *ex-post* abatement costs when compared with pure quantity-based environmental regulation?

Figure 5 summarizes the changes in the distribution ex-post excess abatement costs of hybrid polices when compared to their corresponding pure quantity-based control policy using box-whisker plots. For example, the first two box-whisker plots indicate the change in costs of a second-best hybrid policy with price bounds ($\{\lambda, \underline{P}, \overline{P}\}$) relative to a second-best policy with pure quantity control (λ).

Hybrid policies can bring about reductions in *ex-post* abatement costs, relative to pure quantity control policies, that are both substantial in size and non-negligible in terms of the likelihood for their occurrence. If sectoral shocks on baseline emissions are negatively correlated ($\rho = -0.5$), hybrid policies with price bounds or abatement bounds yields largely similar outcomes with respect to abatement costs under a second-best world (compare the first and third box-whisker plots in Figure 5). In 67.2% (66.2%) of the cases a hybrid policy with price (abatement) bounds reduces *ex-post* abatement costs relative to a pure quantity control. The inability of a hybrid policy with abatement bounds to incorporate information about firms' MAC, however, means that the distribution of abatement costs is slightly more dispersed, as is reflected by a wider inter-quartile range and higher a maximum value.

If baseline emissions across sectors are positively correlated ($\rho = +0.5$), differences between the two types of hybrid policies emerge. While a policy with abatement bounds results in a less dispersed cost distribution due to its ability to directly control the level of abatement, it only brings about costs reductions with 13.9% of the cases. In contrast, a policy with price bounds reduces costs in 49.1% of the cases, however, it creates a more dispersed distribution of cost outcomes with larger probability mass on sizeable cost increases. The reason why a hybrid policy with abatement bounds produces a relatively narrow distribution around zero is simply that it is not very effective.

Under third-best policies, cost reductions with hybrid policies are almost guaranteed. The reasons is, as discussed above, that introducing either type of bounds provide a way to correct the non-optimal allocation factor. For $\rho = -0.5$, in 75% of the cases, cost savings of 70% and larger are achieved. Even if baseline emissions across sectors are positively correlated ($\rho = +0.5$), policies with price or abatement bounds deliver cost savings in 86.5% and 88.2% of the cases, respectively.

5. Conclusion

This paper has examined hybrid emissions trading systems (ETS) with bounds on the price or the quantity of abatement when firms' abatement costs and future emissions are uncertain and when environmental regulation is partitioned. We have investigated the question whether and how the ex-ante and ex-post abatement costs of partitioned climate regulation that is based on an ETS can be reduced by combining price and quantity controls. In our setup, the regulator has to decide ex ante on the allocation of a given environmental target between an ETS and non-ETS partition and on the introduction of lower and upper bounds on the permit price or the quantity of abatement in the ETS partition. Despite the fact that partitioned regulation seems to be the rule rather than the exception in the domain of real-world environmental policies, we are the first to investigate the fundamental public policy question of combining price and quantity controls when regulation is partitioned.

Our analysis has shown that hybrid policies that introduce bounds on the price or the quantity of abatement provide a way to hedge against differences in marginal abatement costs across partitions. Importantly, this can enhance the cost-effectiveness of partitioned environmental regulation by moving the system closer to a first-best outcome where all emitters face identical marginal abatement costs (MACs). We have theoretically characterized ex-ante optimal hybrid ETS policies with price or abatement bounds and shown that it can be optimal to allow MACs to differ across sectors.

We complemented our theoretical analysis of hybrid policies under partitioned environmental regulation with an empirical analysis of EU climate policy investigating the question to what extent introducing hybrid policies in the EU ETS could lower the costs of achieving EU's emissions reduction goals. We have developed a stochastic policy optimization model with equilibrium constraints for the European carbon market that is calibrated based on empirical MAC curves derived from a numerical general equilibrium model and that incorporates uncertainties about future emissions and abatement technologies. We have found that introducing hybrid policies in EU ETS reduces expected excess abatement costs of achieving targeted emissions reductions under EU climate policy by up to 89 percent, depending on the correlation structure between sectoral "no intervention" emissions. While hybrid ETS policies never increase the expected costs, the implications for ex-post costs are a priori unclear. Our quantitative analysis suggests that hybrid policies with price bounds are highly likely to yield sizeable ex-post savings in abatement costs. Hybrid polices with abatement bounds only deliver non-negligible ex-post cost reductions if baseline emissions are negatively correlated as they fail to exploit information on firms' abatement technology.

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.

Our paper is a first step towards analyzing hybrid ETS policies under partitioned environmental regulation. Several directions for future research appear fruitful. First, in would be interesting to study our question in setup that incorporates the marginal benefits from averted pollution and allows for endogenous choice of the overall environmental target. This would essentially imply revisiting the analysis of ex-post efficient permit markets in the context of partitioned environmental regulation. Second, 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. Third, 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. Proof of Proposition 1

We proof the case of a price floor and a minimum bound on abatement (the proof proceeds analogously for the case of a price ceiling and an upper bound on abatement). If an instrument is non-binding there is no reallocation of the emissions budget and hence cost are identical to pure quantity-based regulation. If the price or abatement bound is binding, a change in the emissions level in the ETS sector needs to be balanced by an offsetting change in the non-ETS sector ($\mathrm{d}\overline{e}_T = -\mathrm{d}\overline{e}_N$) such that the economy-wide emissions target holds ($\overline{e} = \overline{e}_T + \overline{e}_N$).

In the case of a binding price floor, the FOC for abatement in sector T ensure equalization of the MAC to the price floor: $\partial C_T/\partial a_T = \underline{P}$. A change in the price therefore requires a change in the allocation factor by moving along the MAC curve: $\mathrm{d}\lambda/(\mathrm{d}\underline{P}) = -(\overline{e}\partial^2 C_T/\partial a_T^2)^{-1}$. Differentiating the regulator's objective (1) for a given state with respect to the carbon price in sector T and substituting terms yields:

$$\frac{\partial C}{\partial \underline{P}} = \left[\frac{\partial C_T}{\partial a_T} - \frac{\partial C_N}{\partial a_N}\right] \frac{1}{\frac{\partial^2 C_T}{\partial a_t^2}} = \left[\underline{P} - P_N\right] \frac{1}{\frac{\partial^2 C_T}{\partial a_T^2}} \ .$$

A price floor below the optimal uniform price implies: $\underline{P} < P_N$. As $\partial C_i/\partial a_i > 0$ and $\partial^2 C_i/\partial a_i^2 > 0$, it follows that $\frac{\partial C}{\partial \underline{P}} < 0$. Introducing a binding price floor below the first-best optimal uniform price therefore decreases total abatement costs.

In the case of binding minimum abatement bound, the change of the allocation factor is determined by the minimum abatement constraint: $e_T^0 - \lambda \overline{e} = \underline{a}$. A change in the minimum abatement level requires changing the allocation factor such that the abatement changes according to: $\mathrm{d}\lambda/(\mathrm{d}\underline{a}) = -\overline{e}^{-1}$. Differentiating (1) with respect to the minimum abatement amount and substituting terms yields: $\partial C/\partial \underline{a} = \partial C_T/\partial a_T - \partial C_N/\partial a_N$. If the minimum abatement amount is below the optimal abatement, strict convexity of abatement cost implies $\partial C_T/\partial a_T < \partial C_N/\partial a_N$ and $\partial C/\partial \underline{a} < 0$. Introducing a binding minimum abatement amount below the first-best optimal abatement amount therefore decreases total abatement cost. □

Appendix B. Derivation of first-order conditions for policy design problem

Hybrid policies with price bounds

Writing expected values in integral notation, the regulator's objective function (as shown in (4)) becomes

$$\begin{aligned}
\min C\left(\lambda, \underline{P}, \overline{P}\right) := & \int_{\underline{b}_N}^{\overline{b}_N} \int_{\underline{\epsilon}(\lambda,\underline{P})}^{\overline{\epsilon}(\lambda,\overline{P})} \left[C_T\left(\tilde{e}_T^0 - \lambda\overline{e}, g_T(\epsilon_T)\right) + C_N\left(\tilde{e}_N^0 - (1-\lambda)\overline{e}, g_N(\epsilon_N)\right)\right] f(\epsilon_T, \epsilon_N)\, \mathrm{d}\epsilon_T \mathrm{d}\epsilon_N \\
& + \int_{\underline{b}_N}^{\overline{b}_N} \int_{\underline{b}_T}^{\underline{\epsilon}(\lambda,\underline{P})} \left[C_T\left(\tilde{e}_T^0 - \underline{\lambda}(\lambda,\underline{P})\overline{e}, g_T(\epsilon_T)\right) + C_N\left(\tilde{e}_N^0 - \left(1 - \underline{\lambda}(\lambda,\underline{P})\right)\overline{e}, g_N(\epsilon_N)\right)\right] f(\epsilon_T, \epsilon_N)\, \mathrm{d}\epsilon_T \mathrm{d}\epsilon_N \\
& + \int_{\underline{b}_N}^{\overline{b}_N} \int_{\overline{\epsilon}(\lambda,\overline{P})}^{\overline{b}_T} \left[C_T\left(\tilde{e}_T^0 - \overline{\lambda}\left(\lambda,\overline{P}\right)\overline{e}, g_T(\epsilon_T)\right) + C_N\left(\tilde{e}_N^0 - \left(1 - \overline{\lambda}\left(\lambda,\overline{P}\right)\right)\overline{e}, g_N(\epsilon_N)\right)\right] f(\epsilon_T, \epsilon_N)\, \mathrm{d}\epsilon_T \mathrm{d}\epsilon_N \, .
\end{aligned} \tag{B.1}$$

Taking the derivative with respect to the fulfillment factor λ yields (applying Leibniz's integral rule):

$$\frac{\partial C}{\partial \lambda} = \int_{\underline{b}_N}^{\overline{b}_N} \int_{\underline{\epsilon}(\lambda,\underline{P})}^{\overline{\epsilon}(\lambda,\overline{P})} \left[\overline{e}\left(\frac{\partial C_N}{\partial a_N} - \frac{\partial C_T}{\partial a_T}\right)\right] f(\epsilon_T, \epsilon_N)\, \mathrm{d}\epsilon_T \mathrm{d}\epsilon_N$$

$$
\begin{aligned}
&+ \int_{\underline{b}_N}^{\overline{b}_N} \left[C_T \left(e_T^0 + \overline{\epsilon} - \lambda \overline{e}, g_T(\overline{\epsilon}) \right) + C_N \left(\tilde{e}_N^0 - (1-\lambda)\overline{e}, g_N(\epsilon_N) \right) \right] \frac{\partial \overline{\epsilon}}{\partial \lambda} (\overline{\epsilon}, \epsilon_N) \, \mathrm{d}\epsilon_N \\
&- \int_{\underline{b}_N}^{\overline{b}_N} \left[C_T \left(e_T^0 + \underline{\epsilon} - \lambda \overline{e}, g_T(\underline{\epsilon}) \right) + C_N \left(\tilde{e}_N^0 - (1-\lambda)\overline{e}, g_N(\epsilon_N) \right) \right] \frac{\partial \underline{\epsilon}}{\partial \lambda} f\left(\underline{\epsilon}, \epsilon_N\right) \mathrm{d}\epsilon_N \\
&+ \int_{\underline{b}_N}^{\overline{b}_N} \int_{\underline{b}_T}^{\underline{\epsilon}(\lambda, \underline{P})} \left[\overline{e} \left(\frac{\partial C_N}{\partial a_N} - \frac{\partial C_T}{\partial a_T} \right) \right] \frac{\partial \underline{\lambda}}{\partial \lambda} f(\epsilon_T, \epsilon_N) \, \mathrm{d}\epsilon_T \mathrm{d}\epsilon_N \\
&+ \int_{\underline{b}_N}^{\overline{b}_N} \left[C_T \left(e_T^0 + \underline{\epsilon} - \underline{\lambda} \overline{e}, g_T(\underline{\epsilon}) \right) + C_N \left(\tilde{e}_N^0 - \left(1-\underline{\lambda}\right)\overline{e}, g_N(\epsilon_N) \right) \right] \frac{\partial \underline{\epsilon}}{\partial \lambda} f\left(\underline{\epsilon}, \epsilon_N\right) \mathrm{d}\epsilon_N \\
&+ \int_{\underline{b}_N}^{\overline{b}_N} \int_{\overline{\epsilon}(\lambda, \overline{P})}^{\overline{b}_T} \left[\overline{e} \left(\frac{\partial C_N}{\partial a_N} - \frac{\partial C_T}{\partial a_T} \right) \right] \frac{\partial \overline{\lambda}}{\partial \lambda} f(\epsilon_T, \epsilon_N) \, \mathrm{d}\epsilon_T \mathrm{d}\epsilon_N \\
&- \int_{\underline{b}_N}^{\overline{b}_N} \left[C_T \left(e_T^0 + \overline{\epsilon} - \overline{\lambda} \overline{e}, g_T(\overline{\epsilon}) \right) + C_N \left(\tilde{e}_N^0 - \left(1-\overline{\lambda}\right)\overline{e}, g_N(\epsilon_N) \right) \right] \frac{\partial \overline{\epsilon}}{\partial \lambda} f(\overline{\epsilon}, \epsilon_N) \, \mathrm{d}\epsilon_N \, . \qquad \text{(B.2)}
\end{aligned}
$$

Define the cost change in sector i by switching from the ex-ante to the endogenous allocation factor under a binding price floor as $\underline{\Delta}_i = C_i(a_i(\lambda), \epsilon_i) - C_i(a_i(\underline{\lambda}(\lambda, \underline{P})), \epsilon_i)$. With a similar definition for $\overline{\Delta}_i$, using the partial derivatives of the threshold level defined in (6b)–(6c), and ordering terms the first order conditions become:

$$
\frac{\partial C}{\partial \lambda} = \overline{e}\, \mathbb{E}\left[\frac{\partial C_N}{\partial a_N} - \frac{\partial C_T}{\partial a_T} \middle| \underline{\epsilon} \leq \epsilon_T \leq \overline{\epsilon} \right] + \mathbb{E}\left[\frac{\omega_U}{\omega_R} \overline{e} \left(\overline{\Delta}_T + \overline{\Delta}_N \right) \middle| \epsilon_T = \overline{\epsilon} \right] - \mathbb{E}\left[\frac{\omega_U}{\omega_R} \underline{e} \left(\underline{\Delta}_T + \underline{\Delta}_N \right) \middle| \epsilon_T = \underline{\epsilon} \right] . \qquad \text{(B.3)}
$$

As the cost difference terms are evaluated at the margin, i.e., at the point the bounds becomes binding, the Δ terms are equal to the marginal cost of the respective sector. The sign for the respective sector is given by the direction of the reallocation: In the case of a binding minimum price, abatement is allocated from the N to the T sector implying an increase (decrease) in T (N) sector's cost; thus: $\underline{\Delta}_T = \frac{\partial C_T}{\partial a_T}$ and $\underline{\Delta}_N = -\frac{\partial C_N}{\partial a_N}$. Likewise a binding price ceiling implies abatement reallocation towards the T sector: $\overline{\Delta}_T = -\frac{\partial C_T}{\partial a_T}$ and $\overline{\Delta}_N = \frac{\partial C_N}{\partial a_N}$. Substituting yields (7a).

For the price floor we have:

$$
\begin{aligned}
\frac{\partial C}{\partial \underline{P}} = &- \int_{\underline{b}_N}^{\overline{b}_N} \left[C_T \left(e_T^0 + \underline{\epsilon} - \lambda \overline{e}, g_T(\underline{\epsilon}) \right) + C_N \left(\tilde{e}_N^0 - (1-\lambda)\overline{e}, g_N(\epsilon_N) \right) \right] \frac{\partial \underline{\epsilon}}{\partial \underline{P}} f\left(\underline{\epsilon}, \epsilon_N\right) \mathrm{d}\epsilon_N \\
&+ \int_{\underline{b}_N}^{\overline{b}_N} \int_{\underline{b}_T}^{\underline{\epsilon}(\lambda, \underline{P})} \left[\overline{e} \frac{\partial \underline{\lambda}}{\partial \underline{P}} \left(\frac{\partial C_N}{\partial a_N} - \frac{\partial C_T}{\partial a_T} \right) \right] f(\epsilon_T, \epsilon_N) \, \mathrm{d}\epsilon_T \mathrm{d}\epsilon_N \\
&+ \int_{\underline{b}_N}^{\overline{b}_N} \left[C_T \left(e_T^0 + \underline{\epsilon} - \underline{\lambda} \overline{e}, g_T(\underline{\epsilon}) \right) + C_N \left(\tilde{e}_N^0 - \left(1-\underline{\lambda}\right)\overline{e}, g_N(\epsilon_N) \right) \right] \frac{\partial \underline{\epsilon}}{\partial \underline{P}} f\left(\underline{\epsilon}, \epsilon_N\right) \mathrm{d}\epsilon_N \qquad \text{(B.4)}
\end{aligned}
$$

Using the derived partial derivatives and using the expectation operator yields equation (7b). The FOC for the price ceiling, (7c), can be derived analogously.

Hybrid policies with abatement bounds

The regulator's objective in the case of a hybrid policy with abatement bounds is given by:

$$
\begin{aligned}
\min C\left(\lambda, \underline{a}, \overline{a}\right) := & \int_{\underline{b}_N}^{\overline{b}_N} \int_{\underline{\epsilon}(\lambda,\underline{a})}^{\overline{\epsilon}(\lambda,\overline{a})} \left[C_T\left(\tilde{e}_T^0 - \lambda\overline{e}, g_T\left(\epsilon_T\right)\right) + C_N\left(\tilde{e}_N^0 - (1-\lambda)\,\overline{e}, g_N\left(\epsilon_N\right)\right)\right] f\left(\epsilon_T, \epsilon_N\right) \mathrm{d}\epsilon_T \mathrm{d}\epsilon_N \\
& + \int_{\underline{b}_N}^{\overline{b}_N} \int_{\underline{b}_T}^{\underline{\epsilon}(\lambda,\overline{a})} \left[C_T\left(\tilde{e}_T^0 - \underline{\lambda}\left(\lambda, \underline{a}\right)\overline{e}, g_T\left(\epsilon_T\right)\right) + C_N\left(\tilde{e}_N^0 - \left(1 - \underline{\lambda}\left(\lambda, \underline{a}\right)\right)\overline{e}, g_N\left(\epsilon_N\right)\right)\right] f\left(\epsilon_T, \epsilon_N\right) \mathrm{d}\epsilon_T \mathrm{d}\epsilon_N \\
& + \int_{\underline{b}_N}^{\overline{b}_N} \int_{\overline{\epsilon}(\lambda,\overline{a})}^{\overline{b}_T} \left[C_T\left(\tilde{e}_T^0 - \overline{\lambda}\left(\lambda, \overline{a}\right)\overline{e}, g_T\left(\epsilon_T\right)\right) + C_N\left(\tilde{e}_N^0 - \left(1 - \overline{\lambda}\left(\lambda, \overline{a}\right)\right)\overline{e}, g_N\left(\epsilon_N\right)\right)\right] f\left(\epsilon_T, \epsilon_N\right) \mathrm{d}\epsilon_T \mathrm{d}\epsilon_N
\end{aligned} \tag{B.5}
$$

Using the partial derivatives of the threshold and endogenous allocation, the derivative of expected cost is given as:

$$
\begin{aligned}
\frac{\partial C}{\partial \lambda} = & \int_{\underline{b}_N}^{\overline{b}_N} \int_{\underline{\epsilon}(\lambda,\underline{a})}^{\overline{\epsilon}(\lambda,\overline{a})} \left[\frac{\partial C_N}{\partial a_N} - \frac{\partial C_T}{\partial a_T}\right] \overline{e} f\left(\epsilon_T, \epsilon_N\right) \mathrm{d}\epsilon_T \mathrm{d}\epsilon_N \\
& + \int_{\underline{b}_N}^{\overline{b}_N} \left[C_T\left(\overline{a}, g_T\left(\overline{\epsilon}\right)\right) + C_N\left(\tilde{e}_N^0 - (1-\lambda)\,\overline{e}, g_N\left(\epsilon_N\right)\right)\right] \overline{e} f\left(\overline{\epsilon}, \epsilon_N\right) \mathrm{d}\epsilon_N \\
& - \int_{\underline{b}_N}^{\overline{b}_N} \left[C_T\left(\underline{a}, g_T\left(\underline{\epsilon}\right)\right) + C_N\left(\tilde{e}_N^0 - (1-\lambda)\,\overline{e}, g_N\left(\epsilon_N\right)\right)\right] \overline{e} f\left(\overline{\epsilon}, \epsilon_N\right) \mathrm{d}\epsilon_N \\
& + \int_{\underline{b}_N}^{\overline{b}_N} \left[C_T\left(\underline{a}, g_T\left(\underline{\epsilon}\right)\right) + C_N\left(\tilde{e}_N^0 - \left(1 - \underline{\lambda}\left(\lambda, \underline{a}\right)\right)\overline{e}, g_N\left(\epsilon_N\right)\right)\right] \overline{e} f\left(\underline{\epsilon}, \epsilon_N\right) \mathrm{d}\epsilon_N \\
& - \int_{\underline{b}_N}^{\overline{b}_N} \left[C_T\left(\overline{a}, g_T\left(\overline{\epsilon}\right)\right) + C_N\left(\tilde{e}_N^0 - \left(1 - \overline{\lambda}\left(\lambda, \overline{a}\right)\right)\overline{e}, g_N\left(\epsilon_N\right)\right)\right] \overline{e} f\left(\overline{\epsilon}, \epsilon_N\right) \mathrm{d}\epsilon_N
\end{aligned} \tag{B.6}
$$

Setting the partial derivative to zero yields equation (9a). (9b) and (9c) are derived similarly.

Appendix C. Equilibrium conditions for numerical general equilibrium model used to derive MAC curves

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. We use the $\perp$ operate to indicate complementarity between equilibrium conditions and variables.[28] Model variables and parameters are defined in Tables C.1, C.3, and C.2.

[28]Following Mathiesen (1985) and Rutherford (1995), we formulate the model as a mixed complementarity problem. A characteristic of many economic models is that they can be cast as a complementary problem, i.e. given a function $F\colon \mathbb{R}^n \longrightarrow \mathbb{R}^n$, 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, $F(z) \geq 0 \perp z \geq 0$. The complementarity format embodies weak inequalities and complementary slackness, relevant features for models that contain bounds on specific variables, e.g. activity levels which cannot a priori be assumed to operate at positive intensity.

Zero-profit conditions for the model are given by:

$$c_r^C \geq PC_r \quad \perp \quad C_r \geq 0 \quad \forall r \tag{C.1}$$

$$c_{ir} \geq PY_{ir} \quad \perp \quad Y_{ir} \geq 0 \quad \forall i, r \tag{C.2}$$

$$c_r^G \geq PG_r \quad \perp \quad G_r \geq 0 \quad \forall r \tag{C.3}$$

$$c_r^I \geq PI_r \quad \perp \quad I_r \geq 0 \quad \forall r \tag{C.4}$$

$$c_{ir}^A \geq PA_{ir} \quad \perp \quad A_{ir} \geq 0 \quad \forall i, r \tag{C.5}$$

$$c_i^T \geq PT_i \quad \perp \quad T_i \geq 0 \quad \forall r \tag{C.6}$$

where c denotes a cost function. Sets $i = 1, \ldots, I$ and $r = 1, \ldots, R$ denotes sectors and regions, respectively. According to the nesting structures shown in Figure C.6b, the expenditure function for consumers is defined as:[29]

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

where

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

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

and where PAE_{ir} denotes the tax inclusive Armington prices defined as:[30] $PAE_{ir} := (1 + ti_{ir})\, PA_{ir}$.

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

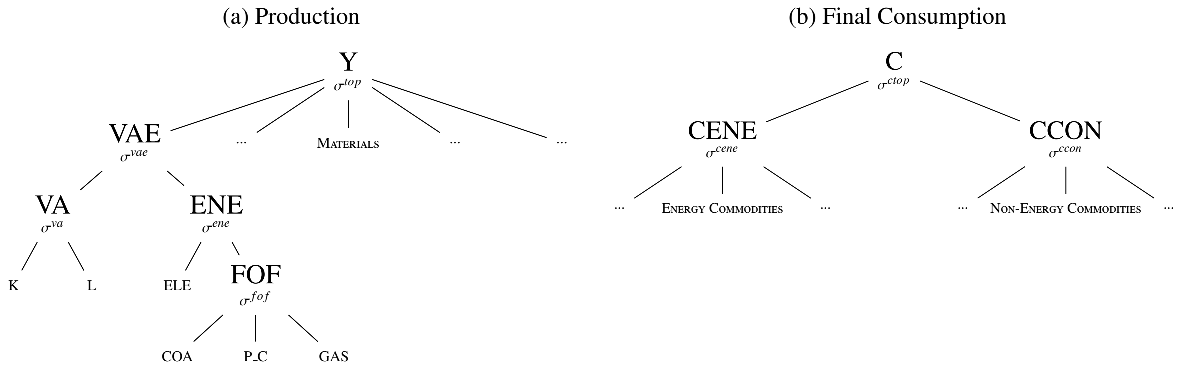
$$c_{ir}^{VAE} := \left[\theta_{ir}^{VAE} (c_{ir}^{VA})^{1-\sigma^{vae}} + \left(1 - \theta_{ir}^{VAE}\right) (c_{ir}^{ENE})^{1-\sigma^{vae}}\right]^{\frac{1}{1-\sigma^{vae}}}$$

$$c_{ir}^{VA} := \left[\theta_{ir}^{VA} \left(\frac{(1 + tl_{ir}) PL_r}{\overline{pl_{ir}}}\right)^{1-\sigma^{va}} + \left(1 - \theta_{ir}^{VA}\right) \left(\frac{(1 + tk_{ir}) PK_r}{\overline{pk_{ir}}}\right)^{1-\sigma^{va}}\right]^{\frac{1}{1-\sigma^{va}}}$$

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

[30] We 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.

Figure C.6: Nested CES structure for production and consumption activities



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

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

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

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

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

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:

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

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 $\overline{L}_r$ and $\overline{K}_r$, respectively, and using

Shephard's lemma, market clearing equations become:

$$Y_{ir} \geq \sum_{s} \frac{\partial c^{A}_{is}}{\partial PY_{ir}} A_{is} + \frac{\partial c^{T}_{i}}{\partial PY_{ir}} T_{i} \qquad \perp \quad PY_{ir} \geq 0 \qquad \forall i, r \tag{C.7}$$

$$A_{ir} \geq \sum_{j} \frac{\partial c_{jr}}{\partial PA_{ir}} Y_{jr} + \frac{\partial c^{C}_{r}}{\partial PA_{ir}} C_{r} + \frac{\partial c^{G}_{r}}{\partial PA_{ir}} G_{r} + \frac{\partial c^{I}_{r}}{\partial PA_{ir}} I_{r} \qquad \perp \quad PA_{ir} \geq 0 \qquad \forall i, r \tag{C.8}$$

$$\overline{L}_{r} \geq \sum_{i} \frac{\partial c_{ir}}{\partial PL_{r}} Y_{ir} \qquad \perp \quad PL_{r} \geq 0 \qquad \forall r \tag{C.9}$$

$$\overline{K}_{r} \geq \sum_{i} \frac{\partial c_{ir}}{\partial PK_{r}} Y_{ir} \qquad \perp \quad PK_{r} \geq 0 \qquad \forall r \tag{C.10}$$

$$T_{i} \geq \sum_{j,r} \frac{\partial c^{A}_{jr}}{\partial PT_{i}} A_{jr} \qquad \perp \quad PT_{i} \geq 0 \qquad \forall r \tag{C.11}$$

$$I_{r} \geq \bar{i}_{r} \qquad \perp \quad PI_{r} \geq 0 \qquad \forall r \tag{C.12}$$

$$C_{r} \geq \frac{INC^{C}_{r}}{PC_{r}} \qquad \perp \quad PC_{r} \geq 0 \qquad \forall r \tag{C.13}$$

$$G_{r} \geq \frac{INC^{G}_{r}}{PG_{r}} \qquad \perp \quad PG_{r} \geq 0 \qquad \forall r\,. \tag{C.14}$$

Private income is given as factor income net of both investment expenditure and a direct tax payment to the government:

$$INC^{C}_{r} := PL_{r}\overline{L}_{r} + PK_{r}\overline{K}_{r} - PI_{r}\bar{i}_{r} - htax_{r}\,. \tag{C.15}$$

Public or government income is given by the sum of all tax revenues:

$$\begin{aligned} INC^{G}_{r} := & \sum_{i} ti_{ir} PA_{ir} \left[\sum_{j} \frac{\partial c_{jr}}{\partial PA_{ir}} Y_{jr} + \frac{\partial c^{C}_{r}}{\partial PA_{ir}} C_{r} + \frac{\partial c^{G}_{r}}{\partial PA_{ir}} G_{r} + \frac{\partial c^{I}_{r}}{\partial PA_{ir}} I_{r} \right] \\ & + \sum_{i} Y_{ir} \left[tl_{r} PL_{r} \frac{\partial c_{ir}}{\partial PL_{r}} + tk_{r} PK_{r} \frac{\partial c_{ir}}{\partial PK_{r}} \right] \\ & + \sum_{i,s} \left[te_{ir} PY_{ir} \frac{\partial c^{A}_{is}}{\partial PY_{ir}} A_{is} + tm_{ir} \left(1 + te_{is}\right) PY_{is} \frac{\partial c^{A}_{ir}}{\partial PY_{is}} A_{ir} \right] \\ & + htax_{r}\,. \end{aligned} \tag{C.16}$$

In summary, $4R + 2I \times R$ zero-profit conditions as given by (C.1)–(C.6) determine an equal number of activity levels, $6R + 2I \times R$ marketing clearing conditions as given by (C.8)–(C.14) determine an equal number of market prices, and $2R$ conditions as given by (C.15)–(C.16) define an equal number of income levels. The square system of model equations then endogenously determines all the above unknowns as functions of benchmark parameters (characterizing the equilibrium before the imposition of a carbon tax) and behavioral parameters (elasticities of production and consumption).

Table C.1: Sets, prices, and quantity variables

Symbol	Description
Sets	
$i \in I$	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
Prices and quantities	
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

Table C.2: Parameter values for substitution elasticities in production and consumption

Parameter	Description	Value
Production		
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
Consumption		
σ^{top}	Energy vs. non-energy consumption	0.25
σ^{ene}	Energy commodities	0.40
σ^{oth}	Non-energy commodities	0.50

Table C.3: Model parameters

Symbol	Description
Elasticity of substitution parameters	
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
Other parameters	
$\bar{i}_r$	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_{ir}^{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

Appendix D. Sampling of MAC curves: additional figures

Figure D.7: Approximation of distribution for technology uncertainty

(a) Original Distribution (b) Reduced Distribution

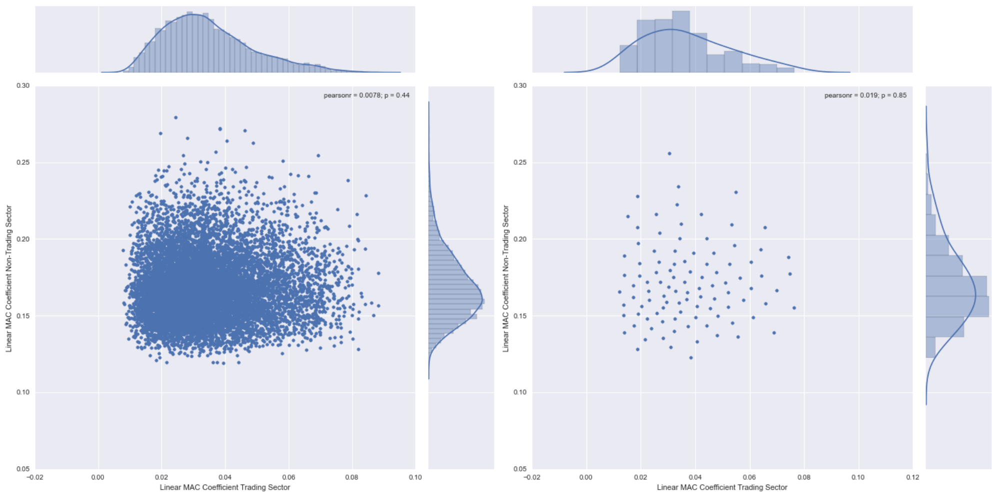


Figure D.8: Approximation of distribution for baseline emissions uncertainty

(a) Original Distribution (b) Reduced Distribution