Time Horizons and Emissions Trading

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DISCUSSION PAPER

Institutt for foretaksøkonomi
Department of Business and Management Science

FOR 2/2024
ISSN: 2387-3000
January 2024

Time Horizons and Emissions Trading

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January 20, 2024

Abstract

We study dynamic cap-and-trade schemes in which a policy of adjustable allowance supply determines the cap on emissions. Focusing on two common supply policies, price and quantity mechanisms, we investigate how the duration of a cap-and-trade scheme affects equilibrium emissions under its cap. More precisely, we consider the reduction in equilibrium emissions realized by shortening the duration of the scheme. We present four main results. First, the reduction in emissions is positive and bounded from below under a price mechanism. Second, the reduction in emissions is bounded from above under a quantity mechanism. Third, these upper and lower bounds coincide when the price and quantity mechanism are similar. Fourth, we identify sufficient conditions for which the reduction in emissions is strictly negative under a quantity mechanism. We quantify our theoretical results for the European Union, the world's largest cap-and-trade scheme to use a quantity mechanism; effects on cumulative EU emissions range from trivial to substantial.

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Keywords: Emissions trading, market-based emissions regulations, policy design

JEL codes: E61, H23, Q58

1 Introduction

Many pollution markets operative today use a policy of adjustable allowance supply to determine the cap on emissions. The usual motivation is that unexpectedly low or high abatement costs would call for changes in emissions which adjustable supply policies can deliver. These policies are thus argued to make the market for allowances more resilient against unanticipated events. Practical examples of adjustable supply policies can be found in the California Cap-and-Trade Program, the Regional Greenhouse Gas Initiative, the European Union's Emissions Trading System, the UK's Emissions Trading Scheme, Germany's National Emissions Trading System, and Québec's cap-and-trade system.

Often, adjustable supply policies determine the emissions cap on the basis of observable conditions in the market for allowances in a rule-based way. This paper focuses on the two most prominent adjustable supply policies of this kind. A *price mechanism* is a policy that increases the number of allowances supplied when the allowance price increases. Alternatively, a *quantity mechanism* is a policy that reduces the supply of allowances when the number of banked allowances goes up. Economist have long advocated both price and quantity measures as means to contain abatement cost uncertainty and variability in cap-and-trade schemes (Roberts and Spence, 1976; Pizer, 2002; Grüll and Taschini, 2011; Abrell and Rausch, 2017; Kollenberg and Taschini, 2016, 2019; Lintunen and Kuusela, 2018; Pizer and Prest, 2020; Quemin and Trotignon, 2021; Perino et al., 2022). Heijmans (2023) shows that price-based supply mechanisms stabilize (marginal) abatement costs indeed; in sharp contrast, he shows that quantity-based mechanisms instead are destabilizing.

Price and quantity mechanisms are intuitively similar. A low price or a large surplus are interpreted to indicate that abatement is cheap, motivating a tightening of the emissions cap.

Both mechanisms thus aim to better align supply and demand in the market for emissions. But, as the results of this paper illustrate, apparent similarities notwithstanding there is a fundamental distinction between the mechanisms. Price mechanisms use prices to update quantities, effectively turning the quantity-instrument that is cap-and-trade into a hybrid policy. Quantity mechanisms instead use quantities to update quantities, doubling down on the quantity aspect of emissions trading. The difference matters.

This paper compares price and quantity mechanisms. We investigate how the duration of a cap-and-trade scheme affects emissions under its cap when the supply of allowances is determined through a price or quantity mechanism. In particular, for any two possible durations of the scheme, we quantify the reduction in equilibrium emissions realized by choosing the shorter, rather than the longer, duration for the policy. We present four main results. First, the reduction in equilibrium emissions is positive and bounded from below under a price mechanism. Second, the reduction in equilibrium emissions is bounded from above (and possibly negative) under a quantity mechanism. Third, these upper and lower bounds coincide when the price and quantity mechanism are comparable (in a way we make formally precise). Fourth, we identify sufficient conditions for which the reduction in equilibrium emissions is strictly negative under a quantity mechanism.

The driving force behind our results is firms' incentive not to hold any allowances once the market ends. An allowance has value only if it can be used to cover emissions. Rather than leave allowances unused by the time the scheme ends, firms use them before the final period to lower abatement costs while they still can. The lifetime of the market for emissions allowances hence impacts firms' dynamic decision problem. More precisely, a shorter time horizon incentivizes firms to use their allowances early on, reducing the amount of allowances banked and exercising downward pressure on the allowance price.[1] Because of the latter effect, a price mechanism reduces the supply of emissions. A quantity mechanism in contrast increases early-periods supply of allowances due to the reduction in banking.

[1] This effect is akin to the green paradox, on which there is a large literature (Van der Ploeg and Withagen, 2012). A similar mechanism also underlies part of the argument in Heijmans (2023).

We derive our results under general assumptions about abatement costs and supply policies. Abatement costs should be convex and increasing, while for price and quantity mechanisms only the signs of the first derivatives of supply functions are specified. The sufficiency of such minimal assumptions, rather than specific functional forms, hints at a deep-rooted distinction between price and quantity mechanisms. Our choice of generality over narrower parametric specifications naturally impedes a welfare analysis. The results in this paper hence do not concern welfare per se bur rather the internal consistency of a set of policies.

There are various interpretations to what we call the duration of the scheme. First, like most policies, the scheme might simply end. For example, the planner could aim to eliminate pollution over time, regulating the transitory period using cap-and-trade. In this most straightforward interpretation, a shortening of the policy's duration may reflect an intention to speed up the decarbonization of the economy in light of increased environmental ambitions. Second, the *effective* duration of the scheme could be dictated by a separate ban on emissions. In this interpretation, the duration of the scheme per se does not change; rather, there is an overlapping policy, independent of the scheme, that eventually dictates the practical lifetime of the scheme. For this case, our results speak to the effect of overlapping policies on equilibrium emissions, an issue also studied – albeit in a somewhat different setup – by Gerlagh et al. (2021) and Perino et al. (2020). Third, the final period could be implied by a policy of retiring emissions allowances (Holland and Moore, 2013). This interpretation is relevant since policymakers often do not intend to keep on supplying new allowances indefinitely. If so, a change in the shelf life of unused allowances effectively implies a change in the duration of the cap-and-trade scheme.

From a policy point of view, our results on quantity mechanisms are arguably most interesting. To put these into context, we also present numerical simulations to illustrate the effect of the time horizon of emissions trading in the world's largest cap-and-trade scheme that uses a quantity mechanism: the European Union's Emissions Trading System (EU ETS).

Our simulations indicate that, in extreme cases, ending the EU ETS in 2035 would lead to an increase in equilibrium emissions of 8,000 MtCO2, or about 85%, compared to a situation in which the scheme exists until 2055. While the EU does not seem to seriously consider ending its ETS by 2035, the magnitude of this effect serves to illustrate the potential force of our theoretical results for practical policies. Even in more realistic scenarios, however, we document potentially steep increases in emissions if the EU were to decarbonize faster. For example, ending the EU ETS – or banning emissions – by 2040 could lead to an increase in cumulative emissions anywhere between 1,250 and 5,500 MtCO2, depending on the interest rate; as a yardstick, Germany's CO2 emissions in 2022 were 655 MtCO2.[2]

Administrative changes to the time horizon of a policy can constitute a major legislative reform. In the EU, for example, no binding final period of its EU ETS is currently foreseen. In such cases, the introduction of a legal final period is so significant a policy change that one cannot reasonably assume the planner to remain committed to the exact supply policy that existed prior to the change of time horizon. This simple recognition would violate our results in a strict sense. We argue, however, that the analysis presented here nevertheless carries an important policy message. Policies aimed at reducing emissions by shortening the time horizon of emissions trading are always complementary to a price-based allowance supply regime; indeed, a price mechanism can even reinforce the emissions reductions that would be obtained under a completely fixed supply schedule. In contrast, without further adjustments a quantity mechanism can work against policies that target the time horizon of emissions trading; indeed, quantity mechanisms may even render such efforts counterproductive. Thus, while a quantity mechanism can be made to work – in the context of a changing time horizon of emissions trading – this may require significant brute-force interventions on the supply side of the market even in periods that are not, in principle, regulatorily affected by the changing time horizon. For the EU, our numerical results offer an indication of how much brute force intervention will be needed. In some sense, price mechanisms interact more naturally with

[2]See the Global Carbon Budget (2022) data set on https://ourworldindata.org/co2-and-greenhouse-gas-emissions.

other parameters of an emissions trading policy than quantity mechanisms; the amount of fine-tuning necessary to make quantity mechanisms work is far greater than that needed to get price mechanisms going.

In a similar way, we argue that the economic argument of this paper has implications beyond our focus on the duration of cap-and-trade schemes. Any policy intended to reduce future emissions exercises a downward pressure on banking incentives and the allowance price in dynamic markets for tradeable emissions allowances. Price mechanisms hence reinforce such policies by supplying fewer allowances while quantity mechanisms counteract them by loosening the cap on emissions. We study the extreme case of a policymaker who directly controls the duration of the scheme for pragmatic reasons: it allows for a precise characterization of the upper and lower bounds on emissions reductions achieved by changing the duration of the policy. In a narrow sense, this paper warns that policies which directly target the timing emissions do not easily combine with cap-and-trade schemes that determine supply through a quantity mechanism. More broadly, it suggests that quantity mechanisms are generally harder to combine with overlapping policies. This broader interpretation supports the claim that price mechanisms have a more general edge over quantity mechanisms. Similarly, none of our results rely on the cap-and-trade scheme regulating emissions.[3]

Perhaps the best-known quantity mechanism currently in use is the EU ETS' Market Stability Reserve (MSR). Our results thus invite particular concern for the European climate agenda. A large number of papers identifies problems with the MSR's quantity-based attempt at market stabilization. Similar in spirit to our Proposition 3, Perino et al. (2020) and Gerlagh et al. (2021) show that overlapping demand-reducing policies can cause an increase in emissions by ETS-regulated industries. Gerlagh and Heijmans (2019) and Quemin and Pahle (2023) discuss how strategic agents may seek to manipulate the MSR to their own advantage. Tietjen et al. (2021) show that the MSR may undesirable consequences for the

[3]While cap-and-trade is mostly used to regulate pollution, tradable quotas also find application in the regulation of fisheries. Moraga and Rapoport (2014) and Hagen (2022) propose a system of tradable immigration quotas to allocate refugee resettlement between countries.

growth path of (expected) allowance prices. Other papers illustrate the large uncertainty about allowance prices and emissions that the complicated design of the MSR generates, see e.g. Gerlagh et al. (2021) and Osorio et al. (2021). Perino et al. (2022) provide an overview of the main strenghts and weaknesses of the MSR.

2 Model

2.1 Building blocks

Consider a dynamic market consisting of a set $N = \{1, 2, ..., n\}$ of polluters, $n > 1$, called firms for simplicity. In each period $t \geq 0$, abatement by firm i is given by $a_{it} = q_{it}^0 - q_{it}$, where q_{it}^0 denotes business-as-usual emissions (i.e. the level emissions in the absence of any policy whatsoever) and $q_{it} \geq 0$ is the actual level of emissions in period t. The cost of abatement is determined by the abatement cost function C_{it} which satisfies $C_{it}(0) = 0$, $C'_{it}(a_{it}) := \frac{\partial C_{it}(a_{it})}{\partial a_{it}} > 0$, and $\frac{\partial^2 C_{it}(a_{it})}{\partial a_{it}^2} \geq 0$. We assume perfect foresight about C_{it} throughout the analysis. This assumption is harsh but inconsequential; nowhere critical does the analysis rely on perfect foresight.

Emissions in periods $0, 1, ..., T$ are regulated through a cap-and-trade scheme, where T is the duration of the scheme which is set at the discretion of the planner; it is allowed that $T \to \infty$. Let s_{it} denote the number of allowances supplied to firm i at the start of period t. Allowances are tradeable on a secondary market where a firm can sell or acquire them at a price p_t which it takes as given.[4] Let m_{it} denote the number of allowances bought on the secondary market by firm i in period t. We assume that every allowance bought must also be sold, so

$$\sum_i m_{it} = 0, \tag{1}$$

[4]The assumption that firms are price takers, while strong, is standard in this literature (*cf.* Pizer, 2002; Hasegawa and Salant, 2014; Abrell and Rausch, 2017; Pizer and Prest, 2020; Holtsmark and Midttømme, 2021; Heijmans, 2023). An interesting study of firm behavior in cap-and-trade markets that are not competitive can be found in Harstad and Eskeland (2010).

for all t. Note from (1) that we rule out exchange rates for allowances other than one, as do most cap-and-trade schemes in practice; Holland and Yates (2015) study optimal exchange rates for tradable emissions quotas. Combining the above, if a firm chooses an amount q_{it} of emissions and buys a total of m_{it} allowances on the secondary market, its total costs in period t are $C_{it}(q_{it}^0 - q_{it}) + p_t m_{it}$.[5]

Emissions may not exceed the supply of allowances. Temporal violations of the periodic caps are facilitated through a banking provision (Kling and Rubin, 1997; Hasegawa and Salant, 2014). Banking by firm i in period t is given by $b_{it} := s_{it} + m_{it} - q_{it}$. The bank of allowances held by firm i at the start of period t is therefore

$$B_{it} := \sum_{s=0}^{t-1} b_{is} = B_{it-1} + b_{it-1} = B_{it-1} + s_{it-1} + m_{it-1} - q_{it-1}, \tag{2}$$

and the total bank of allowances at the start of period t is $B_t := \sum_i B_{it}$. We also assume that borrowing is not allowed,

$$B_{it} \geq 0, \tag{3}$$

for all i and t; this assumption is not necessary, but it is realistic. The effective constraint on emissions by firm i is hence

$$\sum_{s=0}^{t} q_{is} \leq \sum_{s=0}^{t} s_{is} + m_{is}, \tag{4}$$

for all t. Allowances can only be used to cover emissions in the scheme; they have no value after the scheme ends.

In what follows, we investigate the effect of the duration of the cap-and-trade scheme on equilibrium emissions. In particular, we compare emissions between a policy environment in which the final period is T and an alternative environment in which it is $\bar{T} < T$. This is equivalent to a case in which the cap and scheme does not end in period $\bar{T}$ per se but rather one in which, on top of the scheme itself, the planner imposes a binding zero-emissions target

[5]This total cost implicitly assumes trading to be frictionless. For a model of emissions trading with transaction costs, see Baudry et al. (2021).

starting from period $\bar{T}$. Because of this equivalence our results also speak, qualitatively, to a case in which firms face a series of binding but non-zero emissions targets between periods $\bar{T}$ and T (say, a 40% reduction compared to 1990 emissions).

2.2 Firms' problem

In any period t, each firm i seeks to minimize the discounted sum of costs

$$\sum_{\tau=t}^{T} \beta^{\tau-t} \left[C_{i\tau}(q_{i\tau}^0 - q_{i\tau}) + p_\tau m_{i\tau} \right], \tag{5}$$

subject to (1)–(4). Given a vector of prices $p = (p_t)$, let $q_{it}(p_t)$ denote the firm's solution to this problem. Define $q_t(p_t) = \sum_i q_{it}(p_t)$. Convexity of C_{it} implies

$$\frac{\partial q_{it}(p_t)}{\partial p_t} \leq 0 \tag{6}$$

for all $t \leq T$. The inequality is strict whenever $q_{it}(p_t)$ is not a corner solution. As is intuitive, the abatement cost minimizing level of emissions chosen by firm i in period t is decreasing in the prevailing allowance price in that period. For given p_t, define $q_t(p_t) = \sum_i q_{it}(p_t)$ to be total demand for emissions in period t.

Observation 1. *In each period $t \in \{0, ..., T\}$, aggregate demand for emissions $q_{it}(p_t)$ is decreasing in the allowance price p_t.*

Observation 2. *For all $t \in \{0, ..., T-1\}$, cost-minimizing prices co-move between periods:*

$$\frac{\partial p_{t+1}}{\partial p_t} > 0. \tag{7}$$

Observation 2 gives a generalized version of Hotelling's rule. If neither the borrowing nor the secondary market constraint are binding, firms bank allowances until prices rise at the discount rate β. It is well known that binding constraints and other factors cause violations of the rule in its canonical formulation. The literature nevertheless supports the positive co-movement of prices over time.

2.3 Supply mechanisms

Let $s_t = \sum_i s_{it}$ denote the total supply of allowances in period t. We will come to the precise determination of the supply vector s shortly; in any case we assume that $\sum_{s=0}^t s_s < \sum_{s=0}^t q_s^0$ for all t, where $q_t^0 = \sum_i q_{it}^0$. That is, the supply of allowances does not exceed business-as-usual emissions.[6]

The first class of supply mechanisms considered are price mechanisms. To avoid confusion, the supply of allowances under a price mechanism is denoted by s_t^P.

Definition 1 (Price mechanism)**.** *A cap-and-trade scheme operates a* price mechanism *if the supply of allowances in any period t is increasing in the prevailing allowance price p_t. Formally, for any period t and any two price levels p_t and p_t' it holds that $s_t^P(p_t) > s_t^P(p_t')$ if and only if $p_t > p_t'$.*

Price mechanisms were proposed by Roberts and Spence (1976), Pizer (2002), and Abrell and Rausch (2017); practical examples are price collars, as used in California's ETS (Borenstein et al., 2019).[7] We assume that $s_t^P(0) \leq q_t(0)$ and $s_t^P(\infty) \geq q_t(\infty)$ for all t, with a strict inequality for at least one t. While not strictly necessary for our main results, we assume that $s_t^P(p_t)$ is differentiable in p_t to simplify the exposition. We write B_t^P for the bank of allowances when supply is governed by a price mechanism.

[6]The case in which allowance supply exceeds BAU emissions appears empirically irrelevant (Fowlie, 2010; Calel, 2020; Bayer and Aklin, 2020).

[7]The idea, of course, is that the price of emissions allowances says something about the (marginal) cost of abatement firms face; this consideration is not discussed explicitly here as we assume away any informational asymmetries between firms and the government to simplify the exposition. Similar to, but different from, a price mechanism as described here would be a policy that combines a quota with a tax on emissions. Such a policy can also be used to extract firms' private information, see in particular Ambec and Coria (2021) for an exploration of that issue.

Given a price vector p and two periods t_1, t_2 such that $t_1 \leq t_2$, define

$$S^P(t_1, t_2 \mid p) := \sum_{t=t_1}^{t_2} s_t^P(p_t). \tag{8}$$

$S^P(t_1, t_2 \mid p)$ is the number of allowances supplied between periods t_1 and t_2 under a price mechanism when the price vector is p.

The second class of supply mechanisms studied are quantity mechanisms. Let the supply of allowances under a quantity mechanism be denoted by s_t^Q.

Definition 2 (Quantity mechanism)**.** *A cap-and-trade scheme operates a* quantity mechanism *if the supply of allowances in period t is increasing in the aggregate excess supply at the start of period t. That is, for any period t and any two B_t and B_t', it holds that $s_t^Q(B_t) > s_t^Q(B_t')$ if and only if $B_t' > B_t$.*

Quantity mechanisms were studied by Kollenberg and Taschini (2016, 2019), Abrell and Rausch (2017), Lintunen and Kuusela (2018), Pizer and Prest (2020), and Quemin and Trotignon (2021). Examples in practice are abatement bounds (Holt and Shobe, 2016; Abrell and Rausch, 2017), a market stability reserve like the EU's (Gerlagh et al., 2021), or Korea ETS' liquidity provisions (Asian Development Bank, 2018). We assume that $s_t^Q(B_t(p)) \leq q_t(0)$ and $s_t^Q(B_t(p)) \geq q_t(\infty)$ for all p, with a strict inequality for at least one t. While not strictly necessary for our main results, we assume that $s_t^Q(B_t)$ is differentiable in B_t. We also assume that $-1 < \partial s_t^Q / \partial B_t$ for all t to avoid the counter-intuitive scenario in which firms have an incentive to bank less today in order to have more allowances in the future. When supply is governed by a quantity mechanism, we write B_t^Q for the bank of allowances.

Given a price vector p and two periods t_1, t_2 such that $t_1 \leq t_2$, define

$$S^Q(t_1, t_2 \mid p) := \sum_{t=t_1}^{t_2} s_t^Q(B_t^Q(p)). \tag{9}$$

$S^Q(t_1, t_2 \mid p)$ is the number of allowances supplied between periods t_1 and t_2 under a quantity mechanism when the price vector is p.

From the assumption that firms are price-takers follows that each firm, though cognizant of the supply mechanism in place, takes the supply of allowances as given. We also assume that the planner is committed to its supply mechanism. This assumption is strong because it turns the supply of allowances into a mechanical rule rather than a quantity directly at the planner's discretion. However, policy commitment is a common assumption in the literature on emissions trading and supply mechanisms.

The timing of events is as follows. At the start of period t, the planner supplies s_t allowances according to the supply mechanism in place. Firms trade allowances on the secondary market and simultaneously choose their emissions q_t; unused allowances are banked. Markets clear and period $t+1$ begins.

3 Equilibrium

The market is in equilibrium when the supply of emissions allowances is equal to demand subject to all policy constraints; prices adjust to bring about equilibrium. Because firms are price takers, we solve for the competitive market equilibrium.[8]

Our goal is to determine how the duration of the scheme affects equilibrium emissions under its cap. To study this, we compare two scenarios. In one, the scheme ends in period T; in the other, the scheme ends in period $\bar{T}$, where $\bar{T} < T$. We then determine equilibrium emissions in both of these scenarios and calculate the difference. Section 4 states our formal resuls on this difference under price and quantity mechanisms, respectively. Here, we define the equilibrium for different policy scenarions and formalize what we mean by the reduction in equilibrium emissions.

[8]As both our focus on this equilibrium concept and the subsequent argumentation make clear, our results presuppose some sort of market mechanism to be at work in the cap-and-trade scheme. In some jurisdictions, regulated industries may not be market-oriented but strictly regulated by the government; see for example Cao et al. (2021) for a discussion of China's pilot ETS. Our results make no claims about the duration of policy on emissions.

3.1 Price mechanisms

When supply is governed by a price mechanism, the equilibrium is a tuple $\big(p, q(p), s^P(p), T\big)$ such that the price vector p^P yields emissions $q(p^P)$ that solve the firms' optimization problem given supply is equal to $s^P(p^P)$ and the scheme ends in T. $f^P(p^P) \leq T$ denotes the period in which the equilibrium supply of allowances dries up permanently given the equilibrium price vector p^P, so formally $f^P(p^P) := \min\{t : s^P_\tau(p^P) = 0 \,\forall \tau \geq t\}$. When instead the planner chooses to end the scheme in period $\bar{T}$, rather than T, the equilibrium is given by $\big(\bar{p}^P, q(\bar{p}^P), s^P(\bar{p}^P), \bar{T}\big)$.

Given the notation, equilibrium emissions when the scheme ends in T are $\sum_{t=0}^{T} q_t(p^P_t)$; similarly, total emissions when the scheme ends in $\bar{T}$ are $\sum_{t=0}^{\bar{T}} q_t(\bar{p}^P_t)$. Let R^P denote the reduction in equilibrium emissions when the scheme ends in $\bar{T}$, rather than T,

$$R^P(\bar{T}, T) := \sum_{t=0}^{T} q_t(p^P_t) - \sum_{t=0}^{\bar{T}} q_t(\bar{p}^P_t). \tag{10}$$

3.2 Quantity mechanisms

When supply is governed by a quantity mechanism, the market equilibrium is a tuple $\big(p, q(p), s^Q(B(p), T)\big)$ such that the equilibrium price vector p yields emissions $q(p)$ that solve the firms' optimization problem given supply is equal to $s^Q(B(p))$ given that the scheme ends in T. Let $f^Q(p^Q) \leq T$ denote the period in which the equilibrium supply of allowances dries up permanently under a price mechanism, $f^Q(p^Q) := \min\{t : s^Q_t(B(p^Q)) = 0 \,\forall \tau \geq t\}$. When instead the scheme ends in period $\bar{T}$, the market equilibrium is $\big(\bar{p}^Q, q(\bar{p}^Q, \bar{q}), s^Q(B(\bar{p}^Q)), \bar{T}\big)$.

Given the equilibria $\big(p^Q, q(p^Q), s^Q(B(p^Q)), T\big)$ and $\big(\bar{p}^Q, q(\bar{p}^Q, \bar{q}), s^Q(B(\bar{p}^Q)), \bar{T}\big)$, let R^Q denote the reduction in equilibrium emissions when the scheme ends in $\bar{T}$, rather than T,

$$R^Q(\bar{T}, T) := \sum_{t=0}^{T} q_t(p^Q_t) - \sum_{t=0}^{\bar{T}} q_t(\bar{p}^Q_t). \tag{11}$$

The research question of this paper can now be stated concisely as follows. For any two

$\bar{T}$ and T such that $\bar{T} < T$, what are the properties of $R^P(\bar{T}, T)$ and $R^Q(\bar{T}, T)$?

4 Results

This section presents the main results of the paper. All depart from an intuitive first step about equilibrium banking of allowances in period $\bar{T}$. Recall that firms have no incentive to keep allowances beyond the final period of the scheme as allowances have no use other than to cover emissions. At least in period $\bar{T}$, equilibrium banking will therefore be weakly less when the scheme ends in period $\bar{T}$ compared to when it ends in period T. Given supply, this reduction in banking can only come about through an increase in demand, which pushes down the period-$\bar{T}$ allowance price. By our generalized version of Hotelling's rule (Lemma 2), cost-minimizing firms will trade allowances over time in a way that causes this drop in the allowance price in period $\bar{T}$ to trickle down to all other periods. Again given supply, the (weak) reduction in allowance prices in all periods leads to an decrease in banking in all periods. Though supply cannot, under a policy of adjustable allowance supply, be taken as given, Lemmas 1 and 2 extend this intuitive relationship to the case of price and quantity mechanisms.

Lemma 1 (Dynamic price effects under a price mechanism)**.** *Consider a cap-and-trade scheme that operates a price mechanism. For any two periods τ, t, $\tau > 0$ and $t \geq 0$, the bank of allowances B_t^P is increasing in the allowance price p_τ: $\frac{\partial B_t^P(p)}{\partial p_\tau} > 0$.*

Lemma 2 (Dynamic price effects under a quantity mechanism)**.** *Consider a cap-and-trade scheme that operates a quantity mechanism. For any two periods $\tau, t < T$, $\tau > 0$ and $t \geq 0$, the bank of allowances B_t is increasing in the allowance price p_τ: $\frac{\partial B_t^Q(p)}{\partial p_\tau} > 0$.*

Note that the backward propagation of the increase in p_τ that drives the increased banking in all periods t occurs because the increase in p_τ is anticipated. This is the relevant thought experiment for our purposes as we are interested in the effect of the duration of the cap-and-trade scheme on equilibrium prices and banking, and it was assumed that the duration of the scheme is common knowledge starting from period 0. If the increase in p_τ would *not* be known in advance, Lemmas 1 and 2 would apply to banking in periods $t \geq \tau$ only.

4.1 Tight bounds

If allowances are supplied through a price mechanism, the reduction in equilibrium emissions from having the scheme end after $\bar{T}$, rather than T, periods is positive and bounded from below.

Proposition 1. *Consider a cap-and-trade scheme that operates a* price mechanism*. For all $\bar{T}$ and T such that $\bar{T} < T$, the reduction in equilibrium emissions when the scheme ends in period $\bar{T}$, rather than T, satisfies*

$$R^P(\bar{T}, T) \geq S^P(\bar{T}, T \mid p^P) \geq 0. \tag{12}$$

That is, the reduction in equilibrium is bounded from below under a price mechanism. The bound is tight.

Shortening the duration of a cap-and-trade scheme earlier has two mutually reinforcing effects under a price mechanism. First, any allowances that would originally be supplied starting from period $\bar{T}$, $S^P(\bar{T}, T \mid p^P)$, are taken out of the system. Second, firms redistribute their emissions to early periods to avoid holding allowances once the scheme ends: leakage. Higher emissions in early periods suppress the allowance price in those periods. By the mechanics of a price mechanism, this translates into a reduction of supply in the periods leading up to $\bar{T}$, further reducing emissions. The first effect is always present; the second occurs only if firms originally hold a strictly positive bank of allowances at the start of period $\bar{T}$ (i.e. if $B_{\bar{T}}(p^P) > 0$). When supply is determined through a quantity mechanism, the reduction in equilibrium emissions from having the scheme operate for $\bar{T}$, rather than T, periods is bounded from above.

Proposition 2. *Consider a cap-and-trade scheme that operates a* quantity mechanism*. For all $\bar{T}$ and T such that $\bar{T} < T$, the reduction in equilibrium emissions when the scheme ends in period $\bar{T}$, rather than T, satisfies*

$$R^Q(\bar{T}, T) \leq S^Q(\bar{T}, T \mid p^Q). \tag{13}$$

That is, the reduction in equilibrium is bounded from above under a quantity mechanism. The bound is tight.

Shortening the time horizon of emissions has two opposing effects under a quantity mechanism. First, any allowances that would originally be supplied starting from period $\bar{T}$, $S^Q(\bar{T}, T \mid p^Q)$, are eliminated. Second, firms redistribute their emissions to early periods to avoid holding allowances by the time the final period arrives. These two effect are exactly the same for price and quantity mechanisms. However, the mechanics of a quantity mechanism imply that a reduction in banking prior to $\bar{T}$ results in an *increase* in allowance supply in those periods. This effect offsets some (or all) of the emissions reductions achieved by eliminating supply after period $\bar{T}$. The reduction in equilibrium emissions is therefore at most $S^Q(\bar{T}, T \mid p^Q)$, implying an upper bound.

The result that $R^Q(\bar{T}, T)$ is bounded from above but not from below allows, at least in theory, that $R^Q(\bar{T}, T) < 0$. If this happens, equilibrium emissions under the cap will be higher when the duration of the scheme is shorter, meaning that shortening the time horizon of emissions trading is incompatible with strengthened climate ambitions. The question arises whether such a counterintuitive scenario can actually arise. In the next section, we give an affirmative answer to this question. We also identify sufficient conditions under which it does.

4.2 Incompatibility

Fix a duration of the scheme T. Posit a period $T^* < T$ at which, given the duration is T, equilibrium demand is strictly positive while equilibrium supply is already (and permanently) zero. There need not be such a T^*; if it exists, it need not be unique. Assuming at least one exists, set $\bar{T} = T^*$. Formally, one can verify that the conditions on T and $\bar{T}$ thus imposed are:

$$q_{\bar{T}}(p^Q_{\bar{T}}) > 0, \tag{14}$$

and

$$f^Q(p^Q) \leq \bar{T}. \tag{15}$$

Let $\bar{T}$ satisfy (14) and (15). If the planner shortens the duration of the scheme from T to $\bar{T}$ periods, equilibrium emissions strictly increase under a quantity mechanism.

Proposition 3. *Consider a cap-and-trade scheme that operates a* quantity mechanism*. For all $\bar{T}$ and T such that $\bar{T} < T$ and $\bar{T}$ satisfies* (14) *and* (15)*, one has*

$$R^Q(\bar{T}, T) < 0. \tag{16}$$

That is, equilibrium emissions are strictly higher *when the duration of the scheme is shortened from T to $\bar{T}$.*

To understand the result, note that conditions (14) and (15) have two implications. First, by (14), there is no supply of allowances after period $\bar{T}$ even when the scheme ends in T. Hence, shortening the duration of the scheme to $\bar{T}$ periods does not eliminate any supply after period $\bar{T}$. Second, the facts that (i) emissions are strictly positive in period $\bar{T}$ (when the final period is T) and (ii) supply reaches zero before $\bar{T}$ together imply that emissions in $\bar{T}$ must be covered entirely by banked allowances. Shortening the duration of the scheme to $\bar{T}$ periods therefore triggers cost-minimizing firms to deplete their bank of allowances earlier, implying less banking overall and therefore, under a quantity mechanism, increased supply. As no supply is eliminated after period $\bar{T}$ while supply goes up before period $\bar{T}$, equilibrium emissions are strictly higher when the duration of the scheme is $\bar{T}$, rather than $T > \bar{T}$, periods.

4.3 Prices vs. quantities

The foregoing results may seem to favor price over quantity mechanisms from the perspective of emission reductions, though that conclusion is premature. It is possible that emissions reductions under a quantity mechanism exceed those under a price mechanism; this could happen when the lower bound for a price mechanism lies strictly below the upper bound for a quantity mechanism. Here we argue that this possibility is somewhat contrived as it relies on asymmetries in baseline equilibrium allowance supplies.

To formalize this, fix a baseline final period T. Suppose that, given T, the equilibrium supply of allowances in all periods is the same under both a price and a quantity mechanism. Formally, given the baseline final period on emissions T, for all $t \geq 0$ let:

$$s_t^P(p_t^P) = s_t^Q(B_t^Q(p^Q)), \tag{17}$$

where p^P and p^Q again denote baseline equilibrium price vectors under a price and quantity mechanism, respectively. The next result shows that the lower and upper bound on emission reductions under a price and quantity mechanism, respectively, coincide when the baseline equilibria are comparable in this sense of (17).

Proposition 4. *If* (17) *holds for all* $t \leq T$*, then*

$$R^Q(\bar{T}, T) \leq R^P(\bar{T}, T). \tag{18}$$

For similar baseline equilibria, an earlier final period leads to higher emissions reductions under a price mechanism than under a quantity mechanism. Whereas the question of prices versus quantities is as old as environmental economics itself and depends on a score of factors (Weitzman, 1974), the choice between price and quantity mechanisms is much less ambiguous. Under comparable conditions, a price mechanism outperforms a quantity mechanism when it comes to achieving more ambitious environmental goals. See Corollary 4 in Heijmans (2023) for a related result.

4.4 Discussion

In this section, we discuss some of the assumptions maintained throughout the theoretical analysis.

Uncertainty. The model assumes perfect knowledge about present and future abatement costs. This is a strong but largely innocent assumption. It is straightforward to extend the model to one which incorporates asymmetric information and imperfect foresight. In such a model, the quantities $R^P(\bar{T}, T)$ and $R^Q(\bar{T}, T)$ would represent *expected* reductions in equilibrium emissions (with the expectation evaluated at time $t = 0$).

To fix ideas, suppose the true abatement cost function $\tilde{C}_{it}$ depends on a parameter θ_t which is learned only at the start of period t. It is common knowledge that θ_t is drawn from a distribution function $F_t(\theta_t)$. Then one can interpret C_{it} as the expected abatement cost function, evaluated in period 0, i.e. $C_{it}(a_{it}) = \int \tilde{C}_{it}(a_{it} \mid \theta_t)\, dF_t(\theta_t)$. With this re-interpretation of C_{it}, it is clear that the analysis as carried out speaks to expected reductions in equilibrium emissions evaluated at time $t = 0$. The additional assumption one would need in such a model is that the timing of the final period itself does not affect the distribution of θ_t; that is, $F_t(\theta_t)$ remains the same whether the final period is $\bar{T}$ or T. This assumption seems natural.

Net zero. Recall that we can interpret the final period $\bar{T}$ as the point in time at which a complementary policy, independent of the scheme, that bans emissions is implemented. In this interpretation, the issue arises that zero emissions targets are ambiguous. Some argue that *net* zero emissions are the realistic target, implying that a positive amount of emissions is still allowed provided it is compensated for by an equal amount of negative emissions. In this case, even if $\bar{T}$ is interpreted as the period starting from which firms face a complementary zero emissions target, cost-minimizing firms need not necessarily reduce banking all the way to zero by the time period $\bar{T}$ arrives. That said: assuming the cost of negative emissions is increasing and convex, the introduction of a (net) zero emissions target will continue to suppress banking and depress allowances prices, causing supply to go down under a price mechanism and up under a quantity mechanism.

Efficiency. Our results characterize bounds on the reduction in equilibrium emissions from having a cap-and-trade scheme end earlier. They do not discuss how the time horizon of emissions trading affects social welfare. In theory it may be efficient to have higher total emissions that occur earlier in time; the model is silent about this. Given the arguably reasonable assumption that a shorter time horizon of emissions trading (or a complementary emissions-reducing policy) is intended to bring down emissions, the results show how policies that explicitly target the dynamics of emissions can be inconsistent with a market-based emissions cap based on quantities. Indeed, even if it is not total but periodic emissions that we care about (i.e. a flow pollutant model), assuming sufficiently convex damages from pollution likely leads to a reduction in discounted welfare if early-period emissions go up markedly.

Commitment. We assume that the planner is committed to the supply functions s^P and s^Q. If the policy functions s^P and s^Q themselves depend on the final period of the scheme (or the complementary emissions policy in place), the reduction in equilibrium emissions will naturally also depend on changes in the supply functions. Due to the vast number of possible policy changes that could be implemented in this case, we leave the analysis of emissions reductions with a non-committed planner for future work. One way to interpret our results is as indications of how much the planner must adjust the supply function s^Q to avoid an increase in cumulative emissions when the duration of a cap-and-trade scheme is shortened.

Böhringer et al. (2017)

5 Numerical Results

5.1 The EU ETS

To put the results in the previous section into perspective, we simulate the effect of the time horizon of emissions trading on emissions in the EU ETS. First, we briefly describe the exact design of the EU ETS and, in particular, its Market Stability Reserve (MSR). Detailed descriptions of this policy can also be found in Perino (2018), Gerlagh and Heijmans (2019), and Gerlagh et al. (2021).

Regulating roughly 50% of greenhouse gas emissions in the EU, Iceland, Lichtenstein, and Norway, at the time of writing the EU ETS is the world's largest market for carbon in terms of value. While mid-2022, carbon prices in the EU reached record-heights of about 100 €/tCO_2, making EU emissions some of the most expensive in the world, in years prior policymakers had instead been concerned mainly with the consistently low, but highly volatile, price of EU ETS allowances. Indeed, so serious were their concerns that policymakers in 2018 introduced the policy reforms that eventually led to the record-breaking price hike four years later.

The specific policy reform of interest is the introduction and subsequent adjustment of the Market Stability Reserve (MSR). Starting from 2019, the MSR – which functions like a vault – takes in allowances that would otherwise have been supplied whenever the bank of allowances is too large. Specifically, 24% of banked allowances are stored in any year in which the bank of allowances exceeds 833 MtCO_2. In later years, when the bank falls short of 400 MtCO_2, an additional 100 MtCO_2 of allowances is taken from the MSR and auctioned *in addition to* regular supply that year, a practice called backloading. Moreover, when the MSR holds more allowances than were auctioned in the previous year, the excess is written off permanently, implying an effective reduction in overall allowance supply. Because of the latter, supply in the EU ETS is governed by a quantity mechanism according to Definition 2.

We note that, relative to a completely fixed supply scheme, the MSR can only reduce the supply of allowances in the EU ETS for any given time horizon. The results that follow do not assess the effectiveness of the MSR at reducing emissions relative to exogenous supply. Instead, we investigate the effect of the time horizon of emissions on emissions *given* the MSR.

5.2 Calibration

We calibrate a linear demand model,

$$q_t(p_t) = \alpha - \beta \cdot p_t, \tag{19}$$

where q_t denotes emissions in year t and p_t is the allowance price in year t. Though daily data on market prices for allowances are available, emissions are reported on a yearly basis only. We therefore convert daily prices to an annual price by taking a simple average. Using data for the years 2018–2021, we estimate values of 1772 and 8.49 for the coefficients α and β in (19), respectively, implying a choke price of $\alpha/\beta = 208$ €/ton CO_2. These estimates are in general agreement with others in the literature (Gerlagh et al., 2020, 2021; Osorio et al., 2021).

In our calibrations, we impose that equilibrium prices follow Hotelling's rule and rise with the interest rate r,

$$p_{t+1} = (1 + r) \cdot p_t, \tag{20}$$

whenever this does not lead to violations of binding constraints; otherwise, we solve for the allowance price that is the nearest corner solution. Taken together, using observed emissions and the bank of allowances in 2020 as starting point, we find that emissions in the EU ETS end endogenously (i.e. without a final period imposed) sometime between 2045 and 2055, depending on the interest rate. These endogenously determined final years are substantially earlier than those calibrated by Gerlagh et al. (2021); the main explanation is that the EU has tightened allowance supply significantly since Gerlagh et al. published their results.

5.3 Simulations

5.3.1 Cumulative emissions

Figure 1 gives cumulative equilibrium emissions in the EU ETS between the year 2025 and the final year T of the scheme when the interest rate is 1%. Without a final year enforced, emissions end endogenously in the year 2055; in that case, cumulative emissions are about 9,200 MtCO2. In contrast, if emissions were forced to end in 2035, cumulative emissions would be almost 17,000 MtCO2. Strikingly, ending the scheme 20 years earlier could cause in increase in emissions of a whopping 85%. This finding underlines the potential force of our theoretical results.

An 85% increase in cumulative emissions is high; frankly, it seems too high. Two assumptions underlie this result: the low interest rate of 1% and the early final year of 2035. Results for higher interest rates are plotted in different figures, which we will discuss shortly. For now, let us explore more realistic scenarios assuming an interest rate of 1%. Recall that, in the 1% scenario, emissions end endogenously in the year 2055. This is later than the 2050 "net-zero emissions" target to which the EU seems committed. What would happen if the EU implemented 2050 as the final year of its ETS? Figure 1 shows that a hard end on emissions in 2050 will lead to a (marginal) increase in overall emissions. In this sense, targeting 2050 as the year in which emissions should end might be worse for the climate than simple letting the EU ETS run until its endogenous end in 2055. A far more dramatic rise in emissions would occur if instead the EU were to target 2040 as the year in which emissions end, as some policymakers propose; compared to ending the scheme endogenously in 2055, cumulative emissions in the 2040 scenario go up by almost 6,000 MtCO2, from about 9,000 MtCO2 to 15,000 MtCO2.[9]

While our results assuming a 1% interest rate are dramatic, simulated outcomes are fairly sensitive to the interest rate; they become less dramatic as the interest rate increases. Figure 2

[9] To be more precise, EU policymakers proposed slashing emissions by 95% by 2040 (Reuters, June 15, 2023). While 95% is close to a full end of emissions, it clearly is not the same. We present simulation results for reduction targets other than 100% in Section 5.3.3.

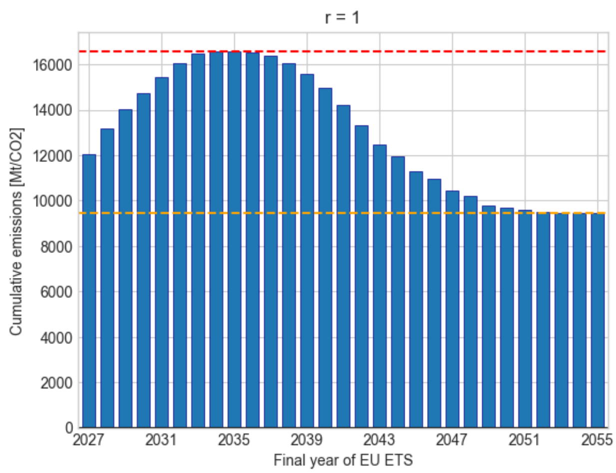

Figure 1: Cumulative emissions in the EU ETS between 2025 and the final year specified on the horizontal axis when the interest rate is 1%. Without a (legally biding) final period, emissions end endogenously in 2055; the dashed orange line gives cumulative emissions in this case. Cumulative emissions are highest when the scheme ends in 2035, reaching a level of emissions indicated by the dashed red line. For any final year prior to 2055, cumulative emissions increase relative to the scenario in which the scheme ends endogenously in 2055.

shows cumulative equilibrium emissions when the interest rate is 2%. In this scenario, the EU ETS ends endogenously in 2049 with emissions totaling 12,500 MtCO2. Imposing a more ambitious end of emissions in, for example, 2040 would increase cumulative emissions to 16,000 MtCO2. When the interest rate is 2%, total emissions are highest if the EU ETS were to end in 2036, reaching a total of 17,000 MtCO2.

Figure 3 presents cumulative equilibrium emissions, as a function of the final year of the scheme, when the interest rate is 3%. Without a binding final year, emissions end endogenously in 2047 and add up to 14,500 MtCO2. By forcefully ending emissions in 2040 instead, cumulative equilibrium emissions would rise to 17,000 MtCO2.

Finally, Figure 4 illustrates cumulative equilibrium emissions in the EU ETS when the interest rate is 4%. In this case, emissions end endogenously in 2045, with cumulative emissions reaching 16,000 MtCO2. Ending the ETS 5 years early would raise cumulative emissions by about 1,500 MtCO2, to 17,500 MtCO2. Choosing a final period prior to 2032 would lead to a reduction in cumulative equilibrium emissions.

Note that the endogenous final year of the EU ETS is decreasing in the interest rate. This

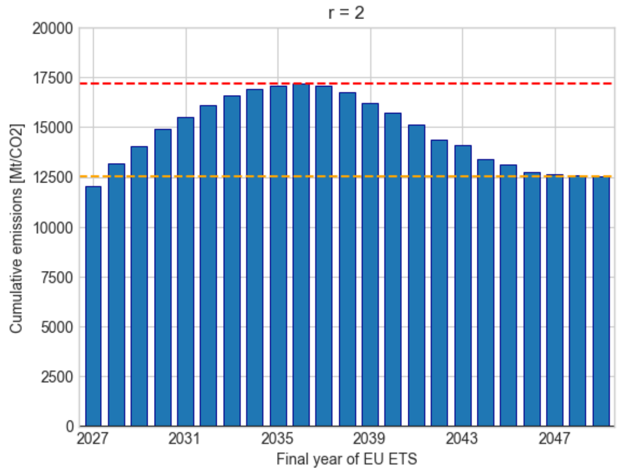

Figure 2: Cumulative emissions in the EU ETS between 2025 and the final year specified on the horizontal axis when the interest rate is 2%. Without a (legally biding) final period, emissions end endogenously in 2049; the dashed orange line gives cumulative emissions in this case. Cumulative emissions are highest when the scheme ends in 2036, reaching a level of emissions indicated by the dashed red line. For any final year between 2030 and 2048, cumulative emissions increase relative to the scenario in which the scheme ends endogenously in 2049.

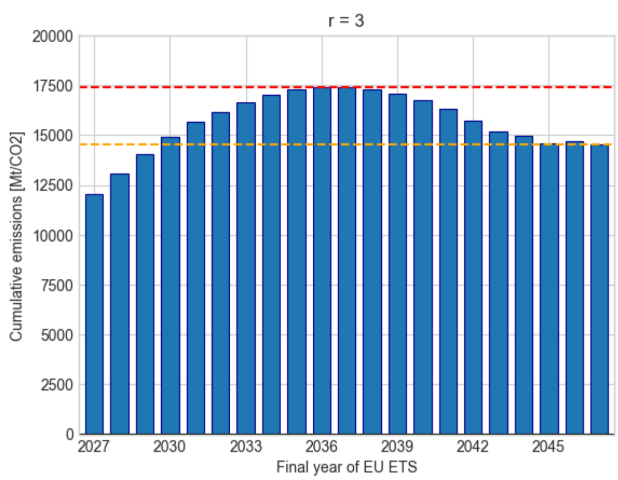

Figure 3: Cumulative emissions in the EU ETS between 2025 and the final year specified on the horizontal axis when the interest rate is 3%. Without a (legally biding) final period, emissions end endogenously in 2047; the dashed orange line gives cumulative emissions in this case. Cumulative emissions are highest when the scheme ends in 2036, reaching a level of emissions indicated by the dashed red line. For any final year between 2030 and 2046, cumulative emissions increase relative to the scenario in which the scheme ends endogenously in 2047.

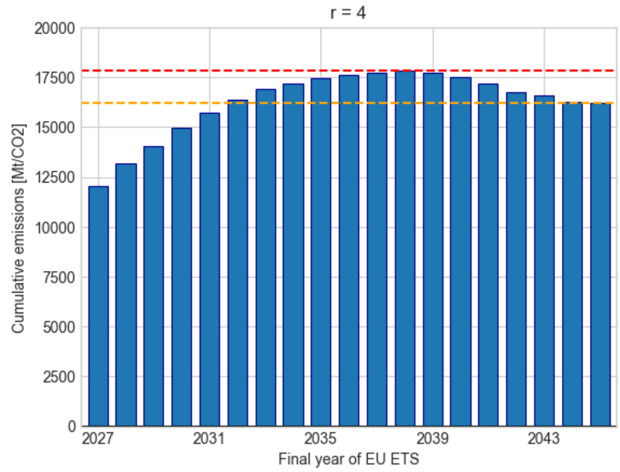

Figure 4: Cumulative emissions in the EU ETS between 2025 and the final year specified on the horizontal axis when the interest rate is 4%. Without a (legally biding) final period, emissions end endogenously in 2045; the dashed orange line gives cumulative emissions in this case. Cumulative emissions are highest when the scheme ends in 2038, reaching a level of emissions indicated by the dashed red line. For any final year between 2032 and 2044, cumulative emissions increase relative to the scenario in which the scheme ends endogenously in 2045.

is intuitive. Recall that emissions stop when allowance prices hit the choke price. Recall also that prices, by assumption, follow Hotelling's Rule and grow with the interest rate. For a given 2022 allowance price the choke price is hence reached faster when the interest rate is higher.

We also observe that the level of cumulative emissions, for a given final year T, is increasing in the interest rate. This is consistent with Corollary 4 in Heijmans (2023), which establishes that emissions in any cap-and-trade scheme where supply is determined by a quantity mechanism are increasing in the interest rate. The higher is the interest rate, the more expensive are emissions in the future relative to emissions today. A high interest rate thus favor emissions in early years, which implies a reduction in allowance banking. When firms bank fewer allowances, the MSR will be smaller; consequently, net supply of emissions is higher. This implies an increase in cumulative emissions, as observed. See also Figure 5, plotting cumulative emissions as a function of the final year for different interest rates.

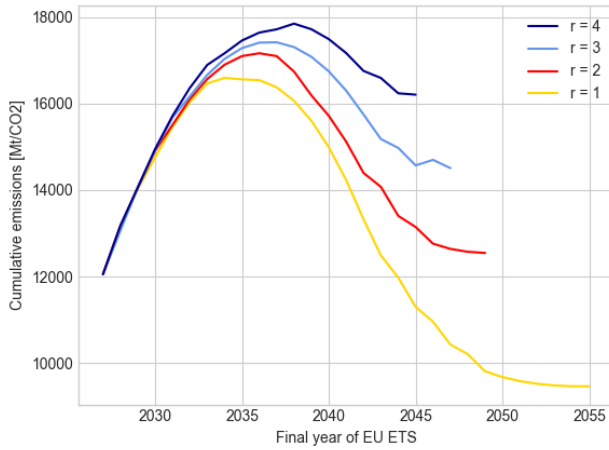

Figure 5: Cumulative emissions in the EU ETS between 2025 and the final year specified on the horizontal axis for different interest rates. A higher interest rate clearly implies higher cumulative emissions for a final year of the EU ETS in which emissions do not end endogenously.

5.3.2 Supply, Demand, and Banking

Figures 1–4 speak to cumulative emissions only. To better understand how these emissions come about, we next present our simulations for (net) allowance supply, demand, and banking in the EU ETS for different scenarios.

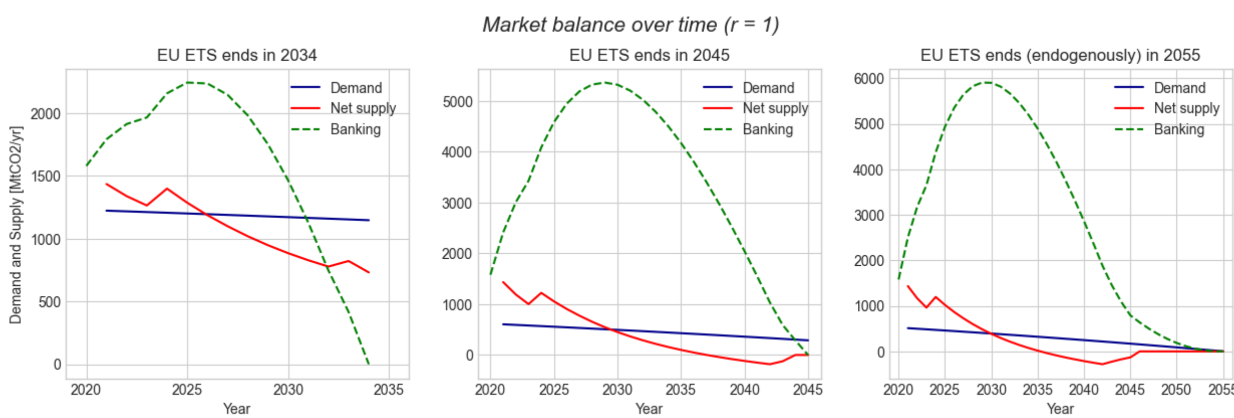

Figure 6: Annual equilibrium emissions, allowance supply, and banking when interest rate is 1% and the scheme ends in 2034, 2045, or 2055, respectively.

Figure 6 plots the development of allowance supply, demand, and banking over time in the EU ETS when the interest rate is 1% and the final year of emissions is 2034, 2045, or

2055, respectively. While the specificities clearly depend upon the final year considered, a number of general trends are clear. First, banking increases substantially in early years and peaks somewhere before 2030; after that, banking declines rapidly. Second, the net supply of allowances tends to be decreasing over time. The slight increase in net supply toward the end of the time horizon considered is due to the release of allowances from the MSR in those years triggered by banking falling below 400 MtCO2. Third, emissions are decreasing almost linearly over time; this is due to the low interest rate. Things look very similar when the interest rate is 2%, results on which we report in Figure 7.

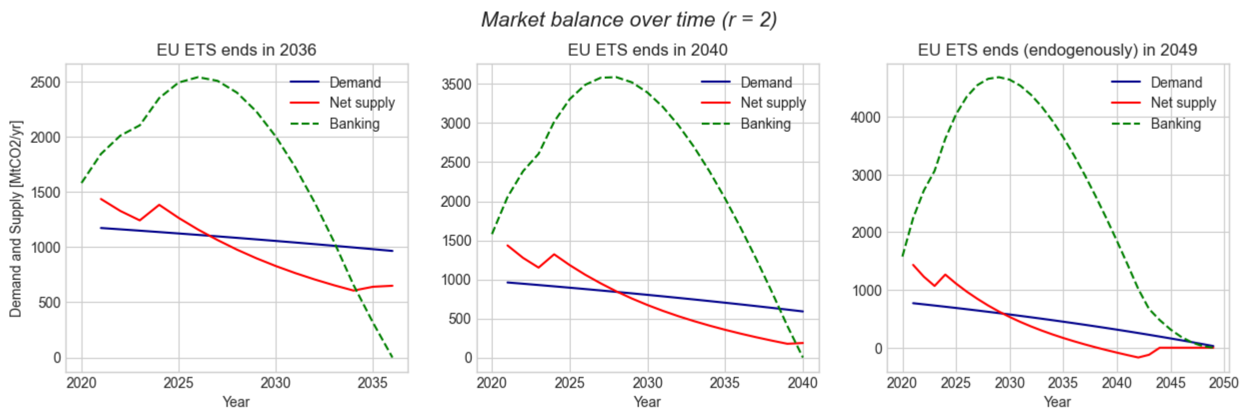

Figure 7: Annual equilibrium emissions, allowance supply, and banking when interest rate is 2% and the scheme ends in 2036, 2040, or 2049, respectively.

When the interest rate is 3% or 4%, trends in banking, emissions, and allowance supply are similar to those when the interest rate is 1% or 2%, see Figures 8 and 9. A comparison between all four figures nevertheless yields an interesting observation. In each figure, the right-hand panel plots equilibrium market conditions when the scheme is allowed to end endogenously. We previously observed that the endogenous final year of emissions is decreasing in the interest rate. From the theoretical analysis, we know that a shorter time of horizon should – under a quantity mechanism – lead to an increase in emissions in early years. Combining these effects, we would expect early emissions (when the scheme is allowed to end endogenously) to be increasing in the interest rate. This prediction is borne out by our simulations: Figures 6–9 clearly show that initial emissions in the right-most panels go up as the interest rate rises.

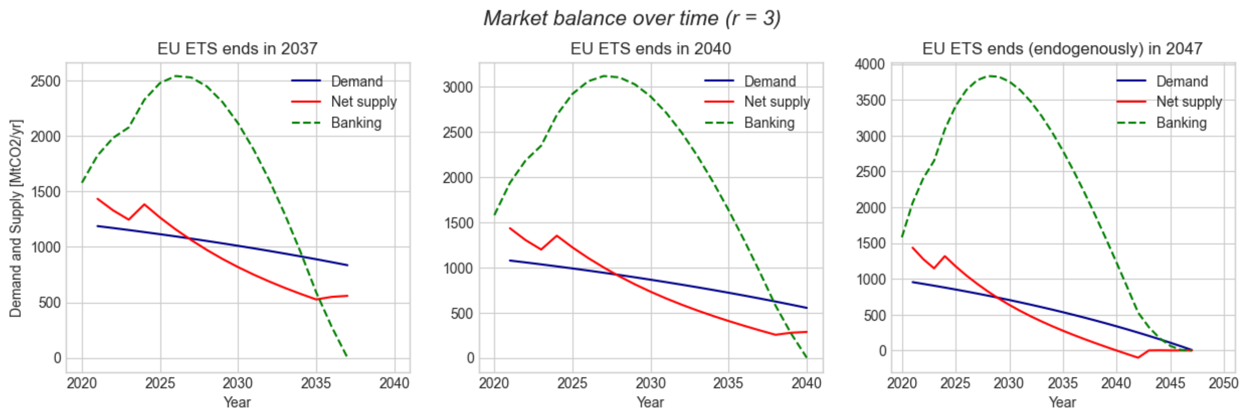

Figure 8: Annual equilibrium emissions, allowance supply, and banking when interest rate is 3% and the scheme ends in 2037, 2040, or 2047, respectively.

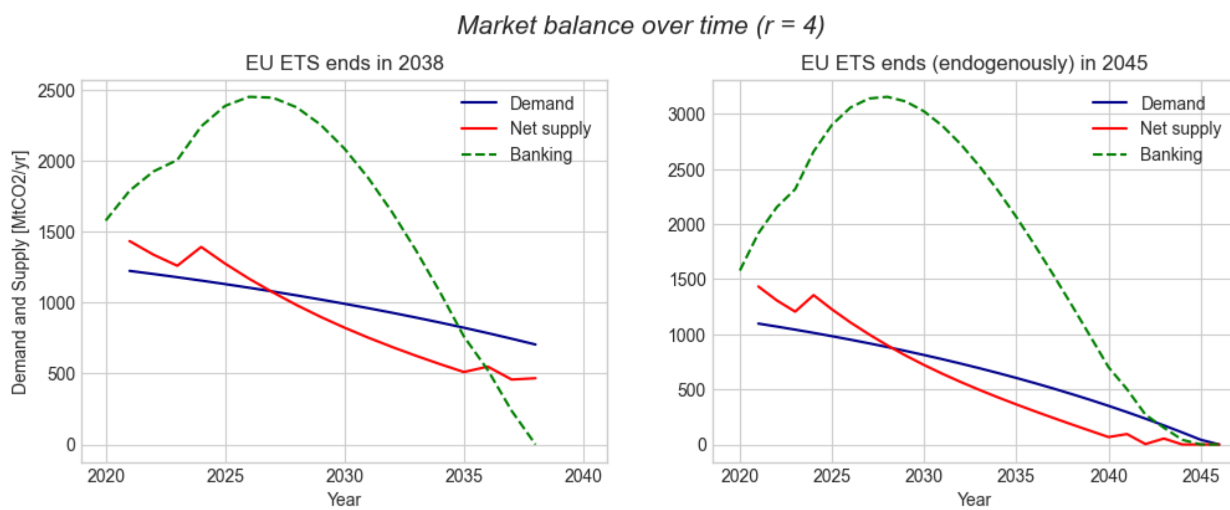

Figure 9: Annual equilibrium emissions, allowance supply, and banking when interest rate is 4% and the scheme ends in 2038 or 2045, respectively.

Note that, in some of the scenarios depicted above, the net supply of allowances dips into negative territories toward the end of the time horizon considered. This is an artifact of the way we define "net supply": it is equal to the actual supply of allowances plus any changes to the number allowances held in the MSR. Net supply can thus become negative when (i) supply itself is already zero, or very low, and (ii) the MSR holds a positive number of allowances, and (iii) banking is sufficiently high to trigger canceling of allowances held in the MSR.

5.3.3 Partial Targets

As was already suggested in the theoretical analysis, an alternative interpretation for the final period T would be the start of an additional policy, independent of the scheme, that (effectively) ends emissions. In this interpretation, a more general scenario is one in which, starting from period T, there is a non-zero binding emissions target that the market may not exceed. The EU, for example, intends to reduce emissions by at least 55% of 1990 levels by 2030. We here present simulations when such interim targets are (also) imposed? All results presented in this section assume an interest rate of 3%.

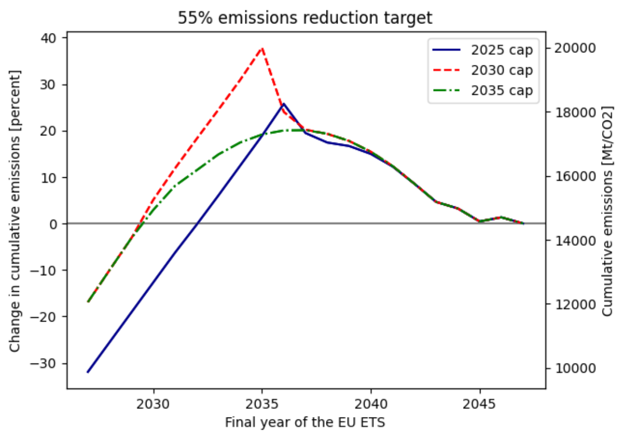

Figure 10: Equilibrium emissions in the EU ETS as a function of the final year of the scheme when, prior to there final year, there also is a binding emissions target requiring at least a 55% reduction in emissions, compared to 2005 levels, that starts in 2025, 2030, or 2035, respectively. The left vertical axis reports the percentage change in cumulative emissions from ending the scheme in year T, rather than letting it end endogenously; the right vertical axis depicts cumulative emissions for the scenario considered.

Figure 10 pictures emissions in the EU ETS as a function of the final year T of the scheme when, prior to T, there also is a binding interim emissions target requiring a 55% (or more) reduction in emissions, compared to 2005 levels.[10] We simulate emissions when the interim targets begin in 2025, 2030, and 2035, respectively. Simulations including interim emissions targets yield roughly the same predictions as those when only a final year is considered. Overall, for later final years of the ETS, emissions seem to be somewhat higher when there

[10]We define partial targets as a percentage of 2005 emissions as this is the year in which the EU ETS began and, consequently, the first year for which ETS emissions data is available.

is an interim target compared to when there is not. This is intuitively plausible: a final year T, combined with a 55% reduction target in year T', should have similar effect on firms' emissions incentives in early years as a final period in year $T'' < T$ without an interim reduction target.

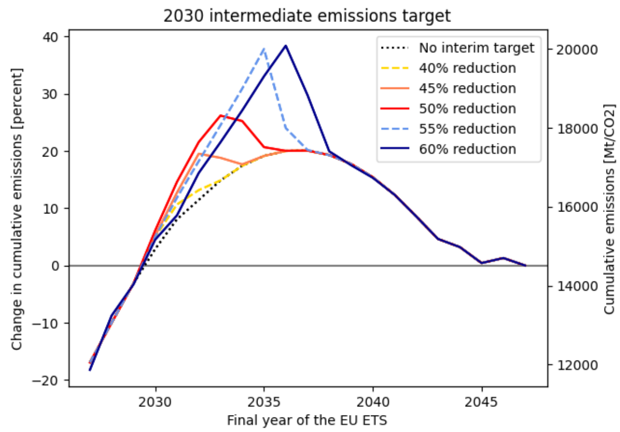

Figure 11: Equilibrium emissions in the EU ETS as a function of the final period when there is a binding emissions target, starting from 2030, that requires a reduction in emissions of at least X% compared to 2005 levels, where $X \in \{40, 45, 50, 55, 60\}$.

Whereas Figure 10 takes as given a 55% reduction target but varies the year in which that targets becomes effective, Figure 11 assumes that an interim emissions targets becomes binding in 2030 but varies the strictness of the target imposed. For late final years, all targets considered yield the same level of cumulative emissions. The reason is that for late final years, 2030 emissions are anyway less than 40% of 2005 levels, so any such interim target is not binding and therefore has no effect on equilibrium outcomes. For final years prior to 2038, different interim targets do yield somewhat different levels of emissions.

6 Conclusions

Market-based, adjustable supply policies input observable conditions in the market for emissions allowances to output a binding cap on emissions. We focus on two of the most common such policies, price and quantity mechanisms, and investigate how the duration of a cap-and-trade scheme affects equilibrium emissions under its cap. We establish a suite of results, all of which appear to favor price-based over quantity-based supply policies.

A natural qualification to the results on quantity mechanisms is the assumed exogeneity of the mechanism to policy changes. One might argue that a rational planner anticipates the effect of advancing the final period and would 'manually' reduce the supply of allowances accordingly. We concur. Even so, a clear benefit of price over quantity mechanisms remains: whereas a quantity mechanism can be made to work after additional measures are taken, a price mechanism takes care of itself.

In a sense, quantity mechanisms misinterpret market signals. They react to a reduction in banking as though it signaled an increase in the demand for emissions whereas, in reality, it is the response to a future (policy-driven) fallout of demand. This points to a more fundamental distinction between price and quantity information. While prices provide an accurate signal of the overall demand for emissions, quantities provide a signal only of *relative* demand, that is, of demand today relative to demand in the future. Being better information aggregators, price signals are favored over quantity signals for market-based policy-updating.

A Proofs

A.1 Firms' dynamic cost-minimization problem

Turning the firm's constrained problem into an unconstrained cost minimization problem, each firm i chooses q_{it} and m_{it} to solve:[11]

$$\begin{aligned} \min_{q_{it}, m_{it}} \sum_{t=0}^{T} \beta^t C_{it}(\bar{q}_{it} - q_{it}) + \sum_t \beta^t p_t m_{it} + \lambda_i \left[\sum_t q_{it} - s_{it} - m_{it} \right] + \sum_t \beta^t \mu_t \left[\sum_i m_{it} \right] \\ + \omega_{it} \left[B_{it} - B_{it-1} - s_{it-1} - m_{it-1} + q_{it-1} \right] + \beta^t \psi_{it} B_{it}. \end{aligned} \tag{21}$$

[11]Without loss of generality, we multiply the shadow values μ_t for the secondary market constraint (1) and ψ_{it} for the borrowing constraint by β^t.

The first-order conditions associated with the cost-minimization problem given by (21) are:

$$-\beta^t C'_{it}(\bar{q}_{it} - q_{it}) + \lambda_i + \omega_{it+1} = 0, \tag{22}$$

$$\beta^t p_t - \lambda_i + \beta^t \mu_t - \omega_{it+1} = 0, \tag{23}$$

$$\omega_{it} - \omega_{it+1} + \beta^t \psi_{it} = 0. \tag{24}$$

Rewriting these first-order conditions gives:

$$C'_{it}(\bar{q}_{it} - q_{it}) + \psi_{it} = \beta C'_{it+1}(\bar{q}_{it+1} - q_{it+1}), \tag{25}$$

for all $t < T$. Moreover, each firm will emit, or abate, until marginal abatement costs roughly equal the allowance price,

$$p_t = C'_{it}(\bar{q}_{it} - q_{it}) - \mu_t, \tag{26}$$

for all $t < T$. We say that prices should roughly equal the allowances price because when $\mu_t \neq 0$, the secondary market constraint is binding and not every firm can buy or sell the number of allowances it wants, driving a wedge between the allowance price and marginal abatement costs.

Observe that cost minimization forces each firm i to choose $m_{it} \leq 0$ for all $t \geq T$; all want to sell allowances if they have some. Combined with the secondary market constraint that $\sum_i m_{it} = 0$ this gives $m_{it} = 0$.

A.2 Proofs

PROOF OF LEMMA 2

Proof. Using (22) and (23) gives:

$$p_t + \mu_t = C'_{it}(\bar{q}_{it} - q_{it}), \tag{27}$$

implying (26). Moreover, combining (24) and (23) yields:

$$p_t + \mu_t + \psi_{it} = \beta p_{t+1} + \beta \mu_{t+1}, \tag{28}$$

so $p_{t+1} = (p_t + \mu_t + \psi_{it})/\beta - \mu_{t+1}$ and this implies (7). $\square$

PROOF OF LEMMA 1

Proof. Since $s_t^P(p_t)$ is increasing in p_t by construction while $q_t(p_t, T)$ is decreasing by (6), banking in period $b_t(p_t)$ is increasing in the allowance price p_t. Recall from (7) that prices co-move across periods. By implication, one has $\frac{\partial p_s}{\partial p_\tau} > 0$ for all $s, \tau \in \{0, 1, ..., T\}$ and therefore,

$$\begin{aligned}\frac{\partial B_t^P}{\partial p_\tau} &= \frac{\partial}{\partial p_\tau}\left[\sum_s^{t-1} s_s^P(p_s) - \sum_s^{t-1} q_s(p_s)\right] \\ &= \sum_s^{t-1} \frac{\partial s_s^P(p_s)}{\partial p_s}\frac{\partial p_s}{\partial p_\tau} - \sum_s^{t-1} \frac{\partial q_s(p_s)}{\partial p_s}\frac{\partial p_s}{\partial p_\tau} > 0.\end{aligned} \tag{29}$$

This establishes that B_t^P is increasing in p_τ for all $t, \tau \in [0, T)$. $\square$

PROOF OF LEMMA 2

Proof. The effect of an increase in the allowance price on first-period banking is straightforward:

$$\frac{\partial B_1^Q(p)}{\partial p_\tau} = \frac{\partial b_0(p_0)}{\partial p_0}\frac{\partial p_0}{\partial p_\tau} = \frac{\partial [s_0^Q - q_0(p_0)]}{\partial p_0}\frac{\partial p_0}{\partial p_\tau} = -\frac{\partial q_0(p_0)}{\partial p_0}\frac{\partial p_0}{\partial p_\tau} \geq 0, \tag{30}$$

where the inequality is strict for all p_0 such that $q_0(p_0,) > 0$ and all $\tau \geq 0$. A little more work is required to determine the sign of $\partial B_t^Q/\partial p_\tau$ for $t > 1$. Recall that the bank of allowances evolves according to $B_t^Q(p) = B_{t-1}^Q(p) + s_{t-1}^Q(B_{t-1}^Q(p)) - q_{t-1}(p_{t-1})$, where s_t depends on B_t^Q

because supply is governed by a quantity mechanism. Hence,

$$\frac{\partial B_t^Q(p)}{\partial p_\tau} = \frac{\partial B_{t-1}^Q(p)}{\partial p_\tau} + \frac{\partial s_{t-1}^Q(B_{t-1}^Q(p))}{\partial p_\tau} - \frac{\partial q_{t-1}(p_{t-1})}{\partial p_\tau} \tag{31}$$

$$= \left(1 + \frac{\partial s_{t-1}^Q(B_{t-1}^Q(p))}{\partial B_{t-1}^Q(p)}\right) \frac{\partial B_{t-1}^Q(p)}{\partial p_\tau} - \frac{\partial q_{t-1}(p_{t-1})}{\partial p_{t-1}} \frac{\partial p_{t-1}}{\partial p_\tau}. \tag{32}$$

The term in parentheses, $1 + \partial s_t^Q / \partial B_t^Q$, is positive by assumption. The final term in (32) is negative by (6) and (7). The only sign left to determine in (32) is hence that of $\partial B_{t-1}^Q / \partial p_\tau$; and this we know for $t = 2$. Using (30), induction on t establishes that

$$\frac{\partial B_t^Q(p)}{\partial p_\tau} \geq 0, \tag{33}$$

for all $t, \tau \in [0, T)$. The inequality is strict for all $p = (p_1, p_2, ...)$ that satisfy $q_t(p_t, T) > 0$ for at least one t. $\square$

PROOF OF PROPOSITION 1

Proof. Two qualitatively distinct scenarios can occur: (i) $B_{\bar{T}}^P(p^P) = 0$ and (ii) $B_{\bar{T}}^P(p^P) > 0$.

In case (i), the equilibrium price vector when the ban on emissions is advanced from T to $\bar{T}$ is the same until period $\bar{T}$: $p_t^P = \bar{p}_t^P$ for all $t < \bar{T}$. This can be proven by contradiction. Suppose $\bar{p}^P \neq p^P$. Then either (a) $\bar{p}_t < p_t$ or (b) $\bar{p}_t > p_t$ for at least one $t < \bar{T}$ which, by Lemma 2, imply that (a) $\bar{p}_t \leq p_t$ or (b) $\bar{p}_t \geq p_t$ for all $t < \bar{T}$. But by Lemma 1, case (a) implies $B_{\bar{T}}(\bar{p}^P) < 0$ whereas case (b) implies $B_{\bar{T}}(\bar{p}^P) > 0$. Either of these violates the requirement that $\bar{p}^P$ is an equilibrium price vector when the final period on emissions is $\bar{p}$. Hence, $\bar{p}^P = p^P$. Equilibrium emissions when the final period is advanced to $\bar{T}$ are therefore equal to:

$$\sum_{t=0}^{\bar{T}} q_t(p^P) = \sum_{t=0}^{\bar{T}} s_t(p_t^P).$$

When the ban is at T instead, equilibrium emissions are:

$$\sum_{t=0}^{T} q_t(p^P) = \sum_{t=0}^{T} s_t(p_t^P).$$

Subtracting the former from the latter gives the reduction in equilibrium emissions:

$$R^P(\bar{T}, T) = \sum_{t=0}^{T} q_t(p^P) - \sum_{t=0}^{\bar{T}} q_t(p^P) = \sum_{t=0}^{T} s_t(p_t^P) - \sum_{t=0}^{\bar{T}} s_t(p_t^P) = S^P(\bar{T}, T \mid p^P).$$

In case (ii), firms originally hold a strictly positive bank of allowances at the start of period $\bar{T}$: $B_{\bar{T}}^P(p^P) > 0$. Equilibrium under the final period $\bar{T}$ is reached when $B_{\bar{T}}(\bar{p}^P) = 0$. By Lemma 1, this implies $p_t^P > \bar{p}_t^P$ for all $t < \bar{T}$. Equilibrium emissions when the final period is $\bar{T}$ are therefore:

$$\sum_{t=0}^{\bar{T}} q_t(\bar{p}^P) = \sum_{t=0}^{\bar{T}} s_t(\bar{p}_t^P).$$

Equilibrium emissions when the final period is T are instead:

$$\sum_{t=0}^{T} q_t(p^P) = \sum_{t=0}^{T} s_t(p_t^P) = \sum_{t=0}^{\bar{T}} s_t(p_t^P) + \sum_{t=\bar{T}+1}^{T} s_t(p_t^P).$$

Subtracting the former from the latter, the reduction in equilibrium emissions when advancing the ban from T to $\bar{T}$ is:

$$\begin{aligned}
R^P(\bar{T}, T) &= \sum_{t=0}^{\bar{T}-1} s_t(p_t^P) + \sum_{t=\bar{T}}^{T} s_t(p_t^P) - \sum_{t=0}^{\bar{T}-1} s_t(\bar{p}_t^P) \\
&= S^p(\bar{T}, T \mid p^P) + \sum_{t=0}^{\bar{T}-1} s_t(p_t^P) - \sum_{t=0}^{\bar{T}-1} s_t(\bar{p}_t^P) \\
&> S^p(\bar{T}, T \mid p^P),
\end{aligned}$$

where the inequality follows from the fact that $p_t^P > \bar{p}_t^P$ for all $t < \bar{T}$ and therefore, by the mechanics of a price mechanism, $s_t(p_t^P) > s_t(\bar{p}_t^P)$ for all $t < \bar{T}$.

In conclusion, either $R^P(\bar{T}, T) = S^p(\bar{T}, T \mid p^P)$ or $R^P(\bar{T}, T) > S^p(\bar{T}, T \mid p^P)$. Since

$S^p(\bar{T}, T \mid p^P) \geq 0$ by construction. Tightness follows from considering the case $B^P_{\bar{T}}(p^P) = 0$. □

PROOF OF PROPOSITION 2

Proof. Two qualitatively distinct scenarios can occur: (i) $B^Q_{\bar{T}}(p^Q) = 0$ and (ii) $B^Q_{\bar{T}}(p^Q) > 0$. Because these scenarios, as well as their analyses, are similar to those discussed in the proof of Proposition 1, we will be short here.

In case (i), $B^Q_{\bar{T}}(p^Q) = 0$ and therefore $\bar{p}^Q_t = p^Q_t$ for all $t < \bar{T}$. The reduction in equilibrium emissions when the final period is $\bar{T}$, compared to when it is T, is therefore:

$$\begin{aligned} R^Q(\bar{T}, T) &= \sum_{t=0}^{T} q_t(p^Q) - \sum_{t=0}^{\bar{T}} q_t(p^Q) \\ &= \sum_{t=0}^{T} s_t(B^Q_t(p^Q)) - \sum_{t=0}^{\bar{T}} s_t(B^Q_t(p^Q)) \\ &= S^Q(\bar{T}, T \mid p^Q). \end{aligned}$$

In case (ii), $\bar{T}$: $B^Q_{\bar{T}}(p^Q) > 0$. Equilibrium under the final period $\bar{T}$ is reached when $B^Q_{\bar{T}}(\bar{p}^Q) = 0$. By Lemmas 2 and 2, this implies $p^Q_t > \bar{p}^Q_t$ for all $t < \bar{T}$. The reduction in equilibrium emissions when the final period is $\bar{T}$, compared to when it is T, is therefore:

$$\begin{aligned} R^Q(\bar{T}, T) &= \sum_{t=0}^{T} q_t(p^Q) - \sum_{t=0}^{\bar{T}} q_t(\bar{p}^Q) \\ &= \sum_{t=0}^{T} s_t(B^Q_t(p^Q)) - \sum_{t=0}^{\bar{T}} s_t(B^Q_t(\bar{p}^Q)) \\ &= S^Q(\bar{T}, T \mid p^Q) + \sum_{t=0}^{\bar{T}} s_t(B^Q_t(p^Q)) - \sum_{t=0}^{\bar{T}} s_t(B^Q_t(\bar{p}^Q)) \\ &< S^Q(\bar{T}, T \mid p^Q), \end{aligned}$$

where the inequality is a consequence of the fact that $p^Q_t > \bar{p}^Q_t$ for all $t < \bar{T}$, so $B^Q_t(p^Q) > B^Q_t(\bar{p}^Q)$ for all $t < \bar{T}$ and therefore, by the mechanics of a quantity mechanism, $s_t(B^Q_t(p^Q)) <$

$s_t(B_t^Q(\bar{p}^Q))$ for all $t < \bar{T}$.

The proof is now complete as we have shown that either $R^Q(\bar{T}, T) = S^Q(\bar{T}, T \mid p^Q)$ or $R^Q(\bar{T}, T) < S^Q(\bar{T}, T \mid p^Q)$, implying that $R^Q(\bar{T}, T)$ is bounded from above by $S^Q(\bar{T}, T \mid p^Q)$. Tightness follows from considering the case $B_{\bar{T}}^Q(p^Q) = 0$. □

PROOF OF PROPOSITION 3

Proof. We know from Proposotion 2 that $R^Q(\bar{T}, T) \leq S^Q(\bar{T}, T \mid p^Q)$. Note, then, that condition (15) gives $S^Q(\bar{T}, T \mid p^Q) = 0$. Moreover, condition (14), combined with (15), gives $B_{\bar{T}}(p^Q) > 0$. The fact that $B_{\bar{T}}(p^Q) > 0$ implies that case (ii) in the proof of Proposotion 2 applies, so $R^Q(\bar{T}, T) < S^Q(\bar{T}, T \mid p^Q)$. We have already established that $S^Q(\bar{T}, T \mid p^Q) = 0$. Hence, $R^Q(\bar{T}, T) < 0$. □

PROOF OF PROPOSITION 4

Proof. From Proposition 1, the reduction in emissions under a price mechanism is bounded from below by $S^P(T, \bar{T} \mid p^P)$. From Proposition 2, the reduction in emissions under a quantity mechanism is bounded from above by $S^Q(T, \bar{T} \mid p^Q)$. The condition that baseline equilibrium supply paths are symmetric means that (17) is satisfied. Now, (17) implies $S^P(T, \bar{T} \mid p^P) = \sum_{\bar{T}}^{T} s_t(p_t^P) = \sum_{\bar{T}}^{T} s_t(B_t^Q(p^Q)) = S^Q(T, \bar{T} \mid p^Q)$ Hence, $R^Q(\bar{T}, T) \leq S^Q(T, \bar{T} \mid p^Q) = S^P(T, \bar{T} \mid p^P) \leq R^P(\bar{T}, T)$, implying the result. □

B Details on the Numerical Analysis

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