Time Horizons And Emissions Trading

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Abstract

I study cap-and-trade schemes where feedback mechanisms from the market for allowances determine, at least in part, the cap on emissions and where the scheme ends with a hard ban on emissions. The effect of bringing forward te ban depends on the supply mechanism in place: under a price mechanism (supply increasing in the allowance price) the reduction in equilibrium emissions from an earlier ban is positive and bounded from below, whereas it is bounded from above and possibly negative under a quantity mechanism (supply decreasing in the surplus of unused allowances). I characterize these bounds and provide conditions under which they coincide. I also identify sufficient conditions for which an earlier ban leads to strictly higher emissions under a quantity mechanism.
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1 Introduction

Policies aimed at controlling externalities often rely on markets. The idea is that market-based policies allow agents covered by the policy to achieve a given goal at least cost. In addition, conditions prevailing in the market may signal valuable information that can be used to update the policy and make it more efficient. Few policies exist in complete isolation, however. It is hence important to understand how a market-based policy functions not just in abstract isolation but also, or perhaps especially, in combination with other policies that affect the market it is based on. This paper investigates that issue.

Perhaps the most typical example of market-based policymaking is emissions trading. In its most basic form, emissions trading, or cap and trade, fixes the total amount of emissions but lets polluters decide on the allocation of emissions under this cap, creating a market for pollution. Additionally, and in contrast the textbook model of a fixed cap, economists have recently come to advocate making the cap endogenous to conditions prevailing in the market for emissions (Holland and Yates, 2015; Abrell and Rausch, 2017; Lintunen and Kuusela,

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2018; Pizer and Prest, 2020). Generally, such proposals come in two forms: price and quantity mechanisms. Under a price mechanism, the cap is increasing in the allowance price; an example is a price collar, used for example in California's ETS (Borenstein et al., 2019). Under a quantity mechanism, the cap is tightened when the surplus of unused allowances increases; an example is a quantity collar, used in the EU ETS (Fell, 2016; Holt and Shobe, 2016). A low price or a large surplus, so the logic goes, mean that the demand for allowances is relatively low. Interpreting a low demand as a signal of low abatement costs, the policymaker responds by tightening the emissions cap (Abrell and Rausch, 2017).

This paper compares price and quantity mechanisms. Consider a cap and trade scheme in which the cap on emissions is determined through either a price or a quantity mechanism. Now suppose that, in addition to the scheme, the policymaker fixes a future point in time starting from which emissions are banned. I show that the reduction in emissions in response to an earlier ban is positive and bounded from below under a price mechanism, whereas it is bounded from above and possibly negative under a quantity mechanism.

The driving force behind my results is firms' incentive not to bank allowances beyond the ban. An allowance has value only if it can be used to cover emissions. Rather than leave allowances unused until emissions are banned, firms use them before the ban is enacted to lower abatement costs when they still can. An earlier ban therefore stimulates firms to use more allowances in early periods, implying less banking and a lower allowance price. Because of the latter effect, a price mechanism – if anything – reinforces the effect on an earlier emissions ban. A quantity mechanism, in contrast, increases the early-period supply of allowances due to the increase in demand, undoing part or all of the emissions reductions achieved due to an earlier ban.

Naturally, the policymaker could remedy the increase in early allowance supply under a quantity mechanism by accompanying the (earlier) future ban on emissions with a 'manual' reduction of the supply path. Even so, my results indicate a benefit of price over quantity mechanisms: whereas a quantity mechanism can be made to work only after additional measures are taken, a price mechanism takes care of itself.

An analysis like this is needed because it focuses on a triplet of climate policies that are often combined: emissions trading, price or quantity mechanisms, and a future ban on emissions. The first, emissions trading for greenhouse gases, is used in more than 30 jurisdictions representing 54% of global GDP (ICAP, 2021). Still more are under way or at least considered. The second, price or quantity mechanisms, complement a large majority of those cap and trade schemes.[1] They have a major impact on existing emissions trading schemes; for example, Borenstein et al. (2019) show that the allowance price in California's cap and trade scheme is determined by the administrative price collar with 98.9 percent probability. The third, a future ban on emissions, reflects the wave of zero emission targets that governments have recently pledged to and which are considered crucial in meeting the Paris Agreement temperature goals (Höhne et al., 2021).

The narrative of a ban on emissions notwithstanding, this paper has broader implications. Any policy intended to reduce emissions in the future exercises a downward pressure on

[1]While not extensive, a list of cap and trade schemes that operate price or quantity mechanisms of the kind studied in this paper includes California's cap and trade scheme, China's National ETS, the EU ETS, Germany's National ETS, Korea's ETS, New Zealand's ETS, the Massachusetts Limits on Emissions from Electricity Generator, the Regional Greenhouse Gas Initiative (RGGI), and Switzerland's ETS.

banking incentives and the allowance price. Due to the lower allowance price, a price mechanism hence reinforces such policies by also supplying fewer allowances. A quantity mechanism instead counteracts the effect by issuing more allowances in early periods due to the reduction in banking. I chose the extreme case of a hard ban on emissions for largely pragmatic reasons. First, as I argue above, future bans actually appear to be popular policy tools (Höhne et al., 2021). Second, a hard ban facilitates precise characterization of the upper/lower bound on emissions reductions. In a narrow sense, this paper warns that future bans on emissions do not easily combine with cap and trade schemes that govern supply through a quantity mechanism. More broadly, it suggests that quantity mechanisms are generally harder to combine with other policies. Either way, price mechanisms appear to have a clear edge over quantity mechanisms.

The paper proceeds as follows. Section 2 sets out the model and defines price and quantity mechanisms formally. Section 3 gives important comparative statics results for the analysis. Section 4 defines the equilibrium in cap and trade schemes under price and quantity mechanisms. Section 5 presents the main results, and Section 6 concludes.

2 Model

I first derive firms' emission decisions from an abatement cost minimization problem. I then formally define and discuss the two supply policies studied.

2.1 Firms' problem

Consider the dynamic abatement cost minimization problem faced by firms. In each period $t \geq 0$, abatement for firm i, with $i = 1, 2, ..., N$, is given by $a_{it} = \bar{q}_{it} - q_{it}$, where $\bar{q}_{it}$ denotes expected 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 $\frac{\partial^2 C_{it}(a_{it})}{\partial a_{it}^2} \geq 0$.

Emissions are regulated through a cap and trade scheme. Let s_{it} denote the number of allowances supplied to firm i in period t. Allowances, once supplied, can be traded on a secondary market where a firm can sell or acquire them at a price p_t which it takes as given. Hence, 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 are $C_{it}(\bar{q}_{it} - q_{it}) + p_t m_{it}$. Firms choose their emissions simultaneously.

Emissions may not, in principle, exceed the supply of allowances. Temporal violations of the periodic cap s_{it} are facilitated through a banking provision (Kling and Rubin, 1997; Hasegawa and Salant, 2014). I define banking by firm i in period t to be $b_{it} := s_{it} + m_{it} - q_{it}$. The bank of allowances held by firm i at the start of period t is therefore $B_{it} := \sum_{s=0}^{t-1} b_{is} = B_{it-1} + b_{it-1} = B_{it-1} + s_{it-1} + m_{it-1} - q_{it-1}$, and the total bank of allowances at the start of period t is $B_t := \sum_i B_{it}$. I also assume that borrowing is not allowed, so $B_{it} \geq 0$ for all i and t. The *dynamic* constraint on emissions by firm i is hence $\sum_{s=0}^{t} q_{is} \leq \sum_{s=0}^{t} s_{is} + m_{is}$ for all t.

On top of the emissions cap, let there be a final period $T > 0$ starting from which emissions are banned; that is, $q_{it} = 0$ for all i and all $t \geq T$. I assume that the ban is a hard constraint, in the sense that firms are not allowed to emit even if they have unused allowances left. A situation in which allowances can be used indefinitely is nested in this model by setting $T \to \infty$. I assume that all firms anticipate the final period T starting from period 0.[2] I colloquially refer to T as the *time horizon of emissions*.

The above elements make for a constrained optimization problem:

$$\begin{aligned}
\min_{q_{it}, m_{it}} \quad & \sum_{t=0}^{\infty} \beta^t \left[C_{it}(\bar{q}_{it} - q_{it}) + p_t m_{it} \right] && (1)\\
\text{subject to} \quad & \sum_s q_{is} \leq \sum_s \left[s_{is} + m_{is} \right], && (2)\\
& \sum_i m_{it} = 0, && (3)\\
& q_{it} = 0, \quad \text{for all} \quad t \geq T, && (4)\\
& B_{it+1} = B_{it} + s_{it} + m_{it} - q_{it}, && (5)\\
& B_{it} \geq 0, && (6)
\end{aligned}$$

for each i and t and where $\beta > 0$ is the discount factor. Constraint (2) says that any individual firm's emissions may not exceed the total number of allowances it owns. Constraint (3) says that, on the secondary market, every allowance bought by one firm must be sold by another.[3] Constraint (4) says that emissions are not allowed starting from period T onward. Finally, (5) is the equation of motion for the bank of allowances and constraint (6) imposes that borrowing allowances from the future is not allowed.

The first-order conditions to this problem are standard and given in the Appendix. For each i and t, let $q_{it}(p_t, T)$ denote the level of emissions that solve the constrained optimization problem above. The assumptions on C_{it} imply

$$\frac{\partial q_{it}(p_t, T)}{\partial p_t} < 0, \tag{7}$$

for all $t < T$. 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 and T, define $q_t(p_t, T) = \sum_i q_{it}(p_t, T)$ to be total demand for emissions in period t.

Lemma 1. *For all $t \in \{0, ..., T-1\}$, aggregate demand for emissions $q_t(p_t, T)$ is decreasing in the allowance price p_t.*

Proof.

$$\frac{\partial q_t(p_t, T)}{\partial p_t} = \sum_i \left[\frac{\partial q_{it}(p_t, T)}{\partial p_t} \right] < 0,$$

where the inequality is an immediate implication of (7). □

[2] This is not really an assumption: simply let $t = 0$ be the first period in which T is common knowledge.

[3] This constraint could be violated if the policymaker, as Holland and Yates (2015) propose, were to put an "exchange rate" on allowances. Because such exchange rates are not common in practice, I stick with constrain (3).

Lemma 2. *For all $t \in \{0, ..., T-1\}$, cost-minimizing prices exhibit positive co-movement over time:*

$$\frac{\partial p_{t+1}}{\partial p_t} > 0. \tag{8}$$

Lemma 2 gives a differential version of Hotelling's rule. It is well known that factors such as asymmetric information (Martimort et al., 2018), arbitrage (Anderson et al., 2018), or rolling planning horizons (Spiro, 2014) can cause violations of the rule in its canonical formulation. Nevertheless, the literature broadly supports the co-movement of prices over time (Anderson et al., 2018; Martimort et al., 2018).

Lemmas 1 and 2 hold for $t \leq T$. The following remarks explain.

Remark 1. *$m_{it} = 0$ for all i and $t \geq T$. That is, firms neither buy nor sell allowances on the secondary market from T onward.*

Remark 2. *The allowance price p_t need not satisfy* (8) *when $t \geq T$. The allowance price comes about through supply and demand on the secondary market. As there is no demand for allowances when $t \geq T$, the allowance price is not properly defined for those periods.*

2.2 Supply mechanisms

Let $s_t = \sum_i s_{it}$ denote the total supply of allowances in period t. I will come to the precise determination of the supply path (s_t) shortly; in any case I assume that $\sum_{s=0}^{t} s_s < \sum_{s=0}^{t} \bar{q}_s$ for all t, where $\bar{q}_t = \sum_i \bar{q}_{it}$. That is, the supply of allowances does not exceed business-as-usual emissions.[4] The exact cap on emissions is assumed to depend on conditions prevailing in the market for allowances. To stay with reality, I limit attention to two classes of supply policies: price and quantity mechanisms.

Definition 1 (Price mechanism)**.** *A cap and trade scheme operates a* price mechanism *if the supply of allowances in any period t is weakly 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 $s_t(p_t) \geq s_t(p'_t)$ if and only if $p_t > p'_t$.*

Examples of price mechanisms include price floors and ceilings (Roberts and Spence, 1976; Fell, 2016; Borenstein et al., 2019). It is assumed that $s_t(0) \leq q_t(0, T)$ and $s_t(\infty) \geq q_t(\infty, T)$ for all t, with a stict inequality for at least one t; this assumption guarantees existence of a positive but finite equilibrium allowance price. While not strictly necessary for my main results, I assume that $s_t(p_t)$ is differentiable in p_t to simplify the exposition.

For any two periods t_1 and t_2, let $S^P(t_1, t_2 \mid p)$ denote the number of a allowances supplied under a price mechanism between periods t_1 and t_2, given the price path $p = (p_t)$:

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

The other type of supply policy considered is a quantity mechanism.

[4] The case in which allowance supply exceeds BAU emissions appears to be empirically irrelevant (Fowlie, 2010; Fowlie et al., 2012; Deschenes et al., 2017; Calel, 2020; Bayer and Aklin, 2020).

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 $s_t(B_t) \geq s_t(B_t')$ if and only if $B_t' > B_t$.*

Examples would be quantity collars (Holt and Shobe, 2016; Abrell and Rausch, 2017), a market stability reserve like the EU's (Fell, 2016), or Korea ETS' liquidity provisions (Asian Development Bank, 2018). I assume that $s_t(B_t(p)) \leq q_t(0, T)$ and $s_t(B_t(p)) \geq q_t(\infty, T)$ for all p, with a strict inequality for at least one t. While not strictly necessary for my main results, I assume that $s_t(B_t)$ is differentiable in B_t. I also assume that $-1 < \partial s_t / \partial B_t$ 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.

For any two periods t_1 and t_2, let $S^Q(t_1, t_2 \mid p)$ denote the number of a allowances supplied under a quantity mechanism between periods t_1 and t_2, given the price path $p = (p_t)$:

$$S^Q(t_1, t_2 \mid p) = \sum_{t=t_1}^{t_2} s_t(B_t(p)). \tag{10}$$

Note that I allow for an exogenous trend to the supply of emissions; price and quantity mechanisms then dictate deviations from the expected path in response to market conditions.

I assume that firms take the supply of allowances as given. This assumptions amounts to saying that each firm is small compared to the size of the market as a whole. In some cases, it is possible that a large firms can exercise market power (Liski and Montero, 2011); I do not investigate the extent to which my analysis generalizes to such environments.[5]

I also assume that the policymaker is committed to the supply mechanism in place. While policy commitment is a strong assumption, it is common in the literature on emissions trading and supply mechanisms (Shobe et al., 2014; Holt and Shobe, 2016; Abrell and Rausch, 2017).

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

3 Dynamic price effects

In this section, I establish that the bank of allowances is increasing in the allowance price under both price and quantity mechanisms. These effects are key drivers of my main results.

Lemma 3 (Dynamic price effects under a price mechanism)**.** *Consider a cap and trade scheme that operates a price mechanism. Fix a final period on emissions T. For any two periods $\tau, t < T$, the bank of allowances B_t is increasing in the allowance price p_τ: $\frac{\partial B_t(p)}{\partial p_\tau} > 0$.*

[5] Assuming that there is an exogenous downward trend in allowance supply such that firms have a clear banking incentive in early periods, market power problems may be of limited concern. Write Liski and Montero (2011), "[...] allocations to early years that exceed the large agent's current emissions do not necessarily lead to market power problems if allocations to later years are below future needs."

Proof. Since $s_t(p_t)$ is increasing in p_t by construction while $q_t(p_t, T)$ is decreasing by (7), banking in period $b_t(p_t)$ is increasing in the allowance price p_t. Recall from (8) 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,

$$\begin{aligned}\frac{\partial B_t}{\partial p_\tau} &= \frac{\partial}{\partial p_\tau}\left[\sum_s^{t-1} s_s(p_s) - \sum_s^{t-1} q_s(p_s, T)\right] \\ &= \sum_s^{t-1} \frac{\partial s_s(p_s)}{\partial p_s}\frac{\partial p_s}{\partial p_\tau} - \sum_s^{t-1} \frac{\partial q_s(p_s, T)}{\partial p_s}\frac{\partial p_s}{\partial p_\tau} > 0.\end{aligned} \tag{11}$$

This establishes that the aggregate bank of allowances B_t is increasing in the allowance price p_τ for all t and τ such that $0 \leq t, \tau < T$. □

Lemma 4 (Dynamic price effects under a quantity mechanism)**.** *Consider a cap and trade scheme that operates a quantity mechanism. Fix a final period on emissions T. For any two periods $\tau, t < T$, the bank of allowances B_t is increasing in the allowance price p_τ:* $\frac{\partial B_t(p)}{\partial p_\tau} > 0$.

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

$$\frac{\partial B_1(p)}{\partial p_\tau} = \frac{\partial b_0(p_0)}{\partial p_0}\frac{\partial p_0}{\partial p_\tau} = \frac{\partial[s_0 - q_0(p_0, T)]}{\partial p_0}\frac{\partial p_0}{\partial p_\tau} = -\frac{\partial q_0(p_0, T)}{\partial p_0}\frac{\partial p_0}{\partial p_\tau} \geq 0, \tag{12}$$

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

$$\frac{\partial B_t(p)}{\partial p_\tau} = \frac{\partial B_{t-1}(p)}{\partial p_\tau} + \frac{\partial s_{t-1}(B_{t-1}(p))}{\partial p_\tau} - \frac{\partial q_{t-1}(p_{t-1}, T)}{\partial p_\tau} \tag{13}$$

$$= \left(1 + \frac{\partial s_{t-1}(B_{t-1}(p))}{\partial B_{t-1}(p)}\right)\frac{\partial B_{t-1}(p)}{\partial p_\tau} - \frac{\partial q_{t-1}(p_{t-1}, T)}{\partial p_{t-1}}\frac{\partial p_{t-1}}{\partial p_\tau}. \tag{14}$$

The term in parentheses, $1 + \partial s_t/\partial B_t$, is positive by assumption. The final term in (14) is negative by (8) and (7). The only sign left to determine in (14) is hence that of $\partial B_{t-1}/\partial p_\tau$. Using (12), induction on t establishes that

$$\frac{\partial B_t(p)}{\partial p_\tau} \geq 0, \tag{15}$$

for all t and τ such that $0 \leq t, \tau < T$. The inequality is strict for all $p = (p_1, p_2, ...)$ that satisfy $q_t(p_t) > 0$ for at least one t. □

The above results are singled out as lemmas due to their supporting role in the analysis. They do, however, come with a clear economic intuition. A higher allowance price reduces the demand for emissions. Under a price mechanism, a higher price also triggers more supply of allowances. These effects combined imply more banking.

Under a quantity mechanism, the logic is more subtle. A higher allowance price in any given period reduces the demand for emissions. This reduction increases the amount of banking in that period, which by construction reduces the supply of allowances in the next. The latter effect, however, is assumed to be less than one-to-one, so the overall bank continues to increase.

4 Equilibrium

The market is in equilibrium when the supply of emissions allowances is equal to demand; prices adjust to brings about equilibrium. Because firms are assumed to be price-takers, I solve the model for a competitive market equilibrium.

4.1 Price mechanisms

Consider a final period on emissions T. The market for allowances is in equilibrium if

$$\sum_{t=0}^{T} q_t(p_t^P, T) = \sum_{t=0}^{T} s_t(p_t^P), \tag{16}$$

where p_t^P is the *baseline* equilibrium allowance price when the scheme operates a price mechanism and the final period on emissions is T.[6] Let $p^P = (p_t^P)$ denote the associated equilibrium price path.

An equilibrium is defined for arbitrary T. Consider then an alternative final period $\bar{T}$ and let $\bar{p}^P$ denote the associated equilibrium price path. That is, $\bar{p}^P$ is the allowance supply path that solves (16) after substituting $\bar{T}$ for T.[7] Now define:

$$R^P(\bar{T}, T) := \sum_{t=0}^{T} s_t(p_t^P) - \sum_{t=0}^{\bar{T}} s_t(\bar{p}_t^P). \tag{17}$$

In words, $R^P(T, \bar{T})$ is the reduction in equilibrium allowance supply when the final period is $\bar{T}$ rather than T, given that supply is governed by a price mechanism.

Under a price mechanism, the supply of allowances depends on the prevailing allowance price. For a given final period on emissions T, let $f^P(T)$ denote the period in which the supply of emissions drops permanently to zero under a price mechanism policy. Formally, $f^P(T)$ is the integer for which the statement that $s_t(p^P) = 0$ if and only if $t \geq f^P(T)$ is true.

[6] An overwhelming oversupply of allowances, such that the number of permits issued exceeds business as usual emissions, might lead to violations of (16). This possibility was ruled out by assumption, and so (16) is an identifying condition for an equilibrium. A similar discussion also applies to equilibrium under a quantity mechanism, presented in the next subsection.

[7] I.e. it solves $\sum_{t=0}^{\bar{T}} q_t(\bar{p}_t^P, \bar{T}) = \sum_{t=0}^{\bar{T}} s_t(\bar{p}_t^P)$.

4.2 Quantity mechanisms

For a final period on emissions T, equilibrium under a quantity mechanism is reached when

$$\sum_{t=0}^{T} q_t(p_t^Q, T) = \sum_{t}^{T} s_t(B_t(p^Q)), \tag{18}$$

where p_t^Q is the baseline equilibrium allowance price in period t under a quantity mechanism and $p^Q = (p_t^Q)$ is the associated price path.

An equilibrium is defined for arbitrary T. Consider then an alternative final period $\bar{T}$ and let $\bar{p}^Q$ denote the associated equilibrium price path. That is, $\bar{p}^Q$ is the allowance supply path that solves (18) after substituting $\bar{T}$ for T.[8] Now define:

$$R^Q(\bar{T}, T) := \sum_{t=0}^{T} s_t(B_t(p^Q)) - \sum_{t=0}^{\bar{T}} s_t(B_t(\bar{p}^Q)). \tag{19}$$

In words, $R^Q(T, \bar{T})$ is the reduction in equilibrium allowance supply when the final period is $\bar{T}$ rather than T, given that supply is governed by a quantity mechanism.

For a given final period on emissions T, let $f^Q(T)$ denote the period in which the supply of allowances dries up permanently under a quantity mechanism. That is, $f^Q(T)$ is the lowest integer such that $s_t(B_t(p^Q)) = 0$ for all $t \geq f^Q(T)$.

5 Results

5.1 Bounds

The precise effect of a change in the timing of the ban depends on details of the supply mechanism and firms' abatement cost functions. Robust qualitative results can nevertheless be obtained. I show that the reduction in equilibrium emissions in response to an earlier ban is positive and bounded from below under a price mechanism. In contrast, it is bounded from above, and possibly negative, under a quantity mechanism.

5.1.1 Price mechanisms

How does an earlier ban on emissions affect equilibrium emissions under a price mechanism?

Proposition 1. *Consider a cap and trade scheme that operates a* price mechanism. *Consider two periods T and $\bar{T}$ such that $\bar{T} < T$. Let p^P denote the equilibrium allowance price path when the final period is T. Then,*

$$R^P(\bar{T}, T) \geq S^P(\bar{T}, T \mid p^P) \geq 0. \tag{20}$$

That is, the reduction in equilibrium emissions in response to an earlier ban is positive and bounded from below under a price mechanism.

[8] I.e. it solves $\sum_{t=0}^{\bar{T}} q_t(\bar{p}_t^Q, \bar{T}) = \sum_{t=0}^{\bar{T}} s_t(B_t(\bar{p}^Q))$.

Proposition 1 says that an earlier ban on emissions unambiguously reduces emissions in cap and trade schemes that operate a price mechanism. Roughly speaking, the price of an allowance is dictated by the opportunity cost of using it now rather that later. In excluding the use of allowances for a wider range of future periods, the earlier ban $\bar{T}$ effectively reduces the opportunity cost of using an allowance today. This translates into a lower allowance price, which, by virtue of the price mechanism, reduces the aggregate supply of allowances and thus emissions.

The lower bound identified in Proposition 1 is intuitive. The minimum emissions reduction due to an earlier ban $\bar{T}$ is simply the number of allowances that would have been supplied from period $\bar{T}$ onward. When the final peroiod is T and the associated equilibrium price path is p^P, this number is given by $S^P(\bar{T}, T \mid p^P)$. The reduction may be larger because firms have no incentive to keep allowances unused beyond the ban. If banking in period $\bar{T}$ is strictly positive at the equilibrium price path p^P, $B_{\bar{T}}(p^P) > 0$, the earlier ban on emissions forces cost-minimizing firms to reshuffle their use of allowances to earlier periods. The associated increase in demand for early period pushes the allowance price down, $\bar{p}^P \leq p^P$, and this further reduces the supply of emissions by virtue of the price mechanism.

5.1.2 Quantity mechanisms

Price mechanism can support an earlier ban on emissions. What about quantity mechanisms?

Proposition 2. *Consider a cap and trade scheme that operates a* quantity mechanism. *Consider two periods T and $\bar{T}$ such that $\bar{T} < T$. Let p^Q denote the equilibrium allowance price path when the final period is T. Then,*

$$R^Q(\bar{T}, T) \leq S^Q(\bar{T}, T \mid p^Q). \tag{21}$$

That is, the reduction in equilibrium emissions in response to an earlier ban is bounded from above (and possibly negative) under a price mechanism.

An earlier ban can reduce emissions under a quantity mechanism, though the reduction is bounded from above. The upper bound has the same intuition as the lower bound for price mechanisms: it is the number of allowances that would, in the baseline equilibrium with final period T and price path p^Q, be supplied between periods $\bar{T}$ and T. Emissions reductions cannot exceed this level because of the way a quantity mechanism is set up. The earlier ban on emissions implies that any allowances firms would have banked beyond period $\bar{T}$ are now used up before that period arrives. Banking in the periods leading up to $\bar{T}$ will hence decrease. Under a quantity mechanism, this reduction in banking causes the supply of allowances to increase, counteracting the reduction achieved by advancing the ban on emissions.

Note that an earlier ban *may* reduce emissions under a quantity mechanism. It does not have to. In the next section, I provide sufficient conditions for the emissions reduction due to an earlier ban to be negative.

5.2 Incompatibility

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

$$q_{\bar{T}}(p^Q_{\bar{T}}, T) > 0, \tag{22}$$

and

$$f^Q(T) \leq \bar{T} < T. \tag{23}$$

If the policymaker advances the emissions ban from period T to this $\bar{T}$, equilibrium emissions will strictly increase.

Proposition 3. *Consider a cap and trade scheme that operates a* quantity mechanism*. Consider two periods T and $\bar{T}$. If T and $\bar{T}$ satisfy* (22) *and* (23)*, then*

$$R^Q(\bar{T}, T) < 0. \tag{24}$$

That is, equilibrium emissions are strictly higher *when the final period is $\bar{T}$ compared to when it is T.*

When the final period is T and the associated equilibrium price path is p^Q, conditions (22) and (23) say that firms hold a strictly positive bank of allowances at the start of period $\bar{T}$. Once the ban on emissions is advanced to $\bar{T}$, firms have no incentive to have a positive bank by the time period $\bar{T}$ arrives. When the final period is $\bar{T}$, equilibrium emissions in all periods leading up to $\bar{T}$ will therefore be higher than equilibrium emissions in those periods when the final period is T. Because higher emissions implies less banking, the quantity mechanism supplies more allowances in those early periods. In combination with condition (23), this implies that supply is higher in *every* period in which there is a positive supply of allowances initially ($f^Q(T) \leq \bar{T}$). Hence, the earlier ban leads to higher emissions in early periods without eliminating any supply later on, causing an increase in emissions overall.

Though precise estimates vary, there is a broad consensus that the supply of allowances in the EU ETS (the world's largest cap-and-trade scheme to operate a quantity mechanism) will end before equilibrium demand reaches zero, implying strictly positive banking after supply dries up (Perino and Willner, 2016; Beck and Kruse-Andersen, 2020; Gerlagh et al., 2020, 2021). This implies that the set of $\bar{T}$s that satisfy conditions (22) and (23) is nonempty; if the EU were to contemplate a hard ban on emissions, it is hence possible that the ban leads to increased emissions overall. Timing matters for EU climate policy.

5.3 Policy choice

The preceding results establish lower (resp. upper) bounds on the reduction in emissions due to an earlier ban under a price (resp. quantity) mechanism. Theoretically, 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 I 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 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:

$$s_t(p_t^P) = s_t(B_t(p^Q)), \tag{25}$$

where p^P and p^Q again denote baseline equilibrium price paths under a price and quantity mechanism, respectively. If (25) is satisfied, I say that the baseline equilibria under a price and quantity mechanism are *symmetric*. 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 symmetric.

Proposition 4. *Consider a baseline final period on emissions T and an earlier period $\bar{T}$ such that $\bar{T} < T$. Let the baseline equilibrium supply path of allowances be symmetric under a price and quantity mechanism. The reduction in equilibrium emissions when the final period is $\bar{T}$, compared to when it is T, is weakly lower under a quantity mechanism than under a price mechanism:*

$$R^Q(\bar{T}, T) \leq R^P(\bar{T}, T). \tag{26}$$

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 (25) is satisfied. Now, using (9) and (10), (25) implies $S^P(T, \bar{T} \mid p^P) = \sum_{\bar{T}}^{T} s_t(p_t^P) = \sum_{\bar{T}}^{T} s_t(B_t(p^Q)) = S^Q(T, \bar{T} \mid p^Q)$. □

For symmetric baseline equilibria, an earlier ban 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; Hoel and Karp, 2001; Montero, 2002; Krysiak, 2008; Alesina and Passarelli, 2014), the choice between price and quantity mechanisms seems unambiguous. A price mechanism clearly outperforms a quantity mechanism.

5.4 Discussion

A natural qualification to the results on quantity mechanisms is the assumed exogeneity of the quantity mechanism to changes in the emissions ban. Some might argue that a rational policymaker will anticipate the effect and 'manually' reduce the supply of allowances accordingly. I concur. Even so, there is a clear benefit of price over quantity mechanisms: whereas a quantity mechanism can be made to work only after additional measures are taken, a price mechanism takes care of itself.

Despite the narrow focus on emissions bans, my results have broader implications. Any policy intended to reduce emissions in the future exercises a downward pressure on banking incentives and the allowance price. A price mechanism hence reinforces such policies. A quantity mechanism instead counteracts the effect by issuing more allowances in early periods due to the reduction in banking. I chose the extreme case of a hard ban on emissions for largely pragmatic reasons. First, as I argue above, emission bans appear to be popular policy tools (Höhne et al., 2021). Second, a hard ban facilitates precise characterizations of the upper/lower bounds on emissions reductions.

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 more efficient information aggregators, price signals are thus favored over quantity signals for market-based policy-updating.

6 Conclusions

I study the effect of a future ban on emissions in the context of a cap and trade policy where the cap on emissions is determined, at least in part, by conditions prevailing in the market for allowances. Under a price mechanism, the supply of allowances is increasing in the allowance price. Under a quantity mechanism, supply is reduced when the surplus of unused allowances increases. I show that the reduction in equilibrium emissions in response to an earlier ban is positive and bound from below under a price mechanism, whereas it is bound from above (and possibly negative) under a quantity mechanism. Precise characterization of these bounds are given, and I identify sufficient conditions for which an earlier ban strictly increases emissions under a quantity mechanism. My results establish that price and quantity mechanisms are not equivalent and, depending on the broader policy environment, should not be used interchangeably.

Key to my results is the way the firms respond to changes in the time horizon of emissions. Because the ban on emissions is a hard constraint, firms use all their allowances before the ban prevents using them for good. An earlier ban therefore leads to higher emissions in early periods, driving down the amount of allowances banked as well as the allowance price. A quantity mechanism translates the associated reduction in banking into a greater supply in early periods. A price mechanism in contrast reduces the supply of allowances in response to the lower allowance price. Price mechanisms thus reinforce the effect of an earlier ban and bring down emissions even further; quantity mechanisms instead counteract the effect of an earlier ban.

At its core, the message of this paper is one about market design. Price and quantity mechanisms are different ways of designing a market for emissions. It is not surprising that the design of a policy can influence its efficiency in achieving a given objective (Weitzman, 1974). What is, perhaps, surprising is the diametrically opposed effects superficially similar policies have on market outcomes.

This paper makes several restrictive assumptions. I consider a particular kind of finite time horizon in which allowances can be used at any time prior to the final period independent of when they were issued. Alternatively, policymakers could write off unused allowances depending on when they were supplied, e.g. allowances can be kept for five years at most. Moreover, I discuss supply mechanisms in the context of a single emissions trading scheme. When multiple cap and trade schemes are linked (Holtsmark and Midttømme, 2021), different incentives may be at work; these are not considered here.

A Appendix

A.1 Firms' dynamic cost-minimization problem

Turning the constrained problem in (1)–(6) into an unconstrained cost minimization problem, each firm i chooses q_{it} and m_{it} to solve:[9]

$$\min_{q_{it},m_{it}} \sum_{t=0}^{T} \beta^t C_{it}(\bar{q}_{it} - q_{it}) + \sum_t \beta^t p_t m_{it} + \lambda_i \left[\sum_t q_{it} - s_{it} - m_{it} \right] + \sum_t \beta^t \mu_t \left[\sum_i m_{it} \right] \\ + \omega_{it} \left[B_{it} - B_{it-1} - s_{it-1} - m_{it-1} + q_{it-1} \right] + \beta^t \psi_{it} B_{it}. \tag{27}$$

The first-order conditions associated with the cost-minimization problem given by (27) are:

$$-\beta^t C'_{it}(\bar{q}_{it} - q_{it}) + \lambda_i + \omega_{it+1} = 0, \tag{28}$$

$$\beta^t p_t - \lambda_i + \beta^t \mu_t - \omega_{it+1} = 0, \tag{29}$$

$$\omega_{it} - \omega_{it+1} + \beta^t \psi_{it} = 0. \tag{30}$$

Rewriting these first-order conditions gives:

$$C'_{it}(\bar{q}_{it} - q_{it}) + \psi_{it} = \beta C'_{it+1}(\bar{q}_{it+1} - q_{it+1}), \tag{31}$$

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

$$p_t = C'_{it}(\bar{q}_{it} - q_{it}) - \mu_t, \tag{32}$$

for all $t < T$. I 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 $m_{it} = 0$, as stated in Remark 1.

A.2 Omitted proofs

PROOF OF LEMMA 2

Proof. Using (28) and (29) gives:

$$p_t + \mu_t = C'_{it}(\bar{q}_{it} - q_{it}), \tag{33}$$

implying (32). Moreover, combining (30) and (29) yields:

$$p_t + \mu_t + \psi_{it} = \beta p_{t+1} + \beta \mu_{t+1}, \tag{34}$$

so $p_{t+1} = (p_t + \mu_t + \psi_{it})/\beta - \mu_{t+1}$ and this implies (8). □

[9] Without loss of generality, I multiply the shadow values μ_t for the secondary market constraint (3) and ψ_{it} for the borrowing constraint by β^t.

PROOF OF PROPOSITION 1

Proof. (i) If baseline equilibrium banking is zero at the start of period $\bar{T}$, $B_{\bar{T}}(p^P) = 0$, equilibrium emissions are *lower* when the final period is $\bar{T}$ compared to when it is T. The reduction in emissions is given by $\Delta^P(T, \bar{T}, \mid p^P)$;

(ii) If baseline equilibrium banking is positive at the start of period $\bar{T}$, $B_{\bar{T}}(p^P) > 0$, equilibrium emissions are *lower* when the final period is $\bar{T}$ compared to when it is T. The reduction in emissions is greater than $\Delta^P(T, \bar{T}, \mid p^P)$.

Part (i). Suppose that $B_{\bar{T}}(p^P) = 0$, so the baseline equilibrium bank of allowances at the start of period $\bar{T}$ is zero. Let $\bar{p}^P$ again denote the equilibrium allowance price path when the time horizon of emissions is $\bar{T}$. By Lemma 3, given the co-movement of allowance prices over time (8), this implies $p_t^P = \bar{p}_t^P$ for all $t < \bar{T}$ (a point that can be readily established by contradiction). In this case, the aggregate reduction in emissions when tightening the time horizon of emissions from T to $\bar{T}$ is therefore given by:

$$\sum_{t=\bar{T}}^{f^P(T)} s_t(p_t^P) > 0, \tag{35}$$

which by definition is equal to $\Delta^P(T, \bar{T} \mid p^P)$.

Part (ii). Suppose that $B_{\bar{T}}(p^P) > 0$, meaning that in the baseline equilibrium firms hold a strictly positive bank of allowances at the start of period $\bar{T}$. Equilibrium under the final period $\bar{T}$ is reached when $B_{\bar{T}}(\bar{p}^P) = 0$, see (**??**). By Lemma 3, this implies $p_t^P > \bar{p}_t^P$ for all $t < \bar{T}$. In this case, the aggregate reduction in emissions when tightening the time horizon of emissions from T to $\bar{T}$ is therefore given by:

$$\sum_{t=\bar{T}}^{f^P(T)} s_t(p_t^P) + \sum_{t=0}^{\bar{T}-1} s_t(p_t^P) - \sum_{t=0}^{\bar{T}-1} s_t(\bar{p}_t^P) > \sum_{t=\bar{T}}^{f^P(T)} s_t(p_t^P) > 0, \tag{36}$$

where the first inequality follows from the facts that $p_t^P > \bar{p}_t^P$ for all $t < \bar{T}$ and supply is governed by a price mechanism. $\square$

PROOF OF PROPOSITION 2

Proof. To prove the proposition, note that essentially two cases can arise: (i) the baseline equilibrium ban of allowances is zero in period $\bar{T}$; or (ii) the baseline bank of allowances is positive in period $\bar{T}$. Under the conditions specified in the propositions, one can write out emissions and obtains:

(i) If baseline equilibrium banking is zero at the start of period $\bar{T}$, $B_{\bar{T}}(p^Q) = 0$, equilibrium emissions are *lower* when the final period is $\bar{T}$ compared to when it is T. The reduction in aggregate emissions is equal to $\Delta^Q(T, \bar{T} \mid p^Q)$;

(ii) If baseline equilibrium banking is positive at the start of period $\bar{T}$, $B_{\bar{T}}(p^Q) > 0$, equilibrium emissions can be *lower or higher* when the final period is $\bar{T}$ compared to when it is T. Either way, the reduction in aggregate emissions is less than $\Delta^Q(T, \bar{T} \mid p^Q)$.

Part (i). Suppose that $B_{\bar{T}}(p^Q) = 0$, so the baseline equilibrium bank of allowances at the start of period $\bar{T}$ is zero. Let $\bar{p}^Q$ again denote the equilibrium allowance price path when the final period is $\bar{T}$. In this case, the aggregate reduction in emissions when tightening the time horizon of emissions from T to $\bar{T}$ is given by:

$$\sum_{t=\bar{T}}^{f^Q(T)} s_t(B(p^P)) > 0, \tag{37}$$

which is $\Delta^Q(T, \bar{T} \mid p^Q)$.

Part (ii). Next suppose that $B_{\bar{T}}(p^Q) > 0$, so the baseline equilibrium bank of allowances at the start of period $\bar{T}$ is positive. Let $\bar{p}^Q$ again denote the equilibrium allowance price path when the final period is $\bar{T}$. Because equilibrium under the tighter horizon $\bar{T}$ requires $B_{\bar{T}}(\bar{p}^Q) = 0$, it holds that $\bar{p}_t^Q < p_t^Q$ for all $t < \bar{T}$. In this case, the aggregate reduction in emissions when tightening the time horizon of emissions from T to $\bar{T}$ is hence given by:

$$\sum_{t=\bar{T}}^{f^Q(T)} s_t(B(p^P)) + \sum_{t=0}^{\bar{T}-1} \left(s_t(B_t(p^Q)) - s_t(B_t(\bar{p}^Q)) \right) \lesseqgtr 0. \tag{38}$$

The sign of (38) is ambiguous. While tightening the time horizon of emissions from T to $\bar{T}$ causes an undisputed reduction of emissions between periods $\bar{T}$ to T, emissions may increase in periods leading up to period $\bar{T}$ when the time horizon gets tightened due to firms' incentives not to bank allowances beyond the final period. Thus, if it so happens that the baseline equilibrium bank of allowances is positive at the start of period $\bar{T}$ (Case 2), early-period emissions increase in response to the shorter time horizon. Under a quantity mechanism, this effect is further reinforced by the increase in allowance supply in those periods. If this effect, the second part on the left-hand side of (38), outweighs the reduction in emissions *after* period $\bar{T}$, emissions overall rise once the time horizon gets tightened. □

PROOF OF PROPOSITION 3

Proof. Equilibrium under the restricted final period $\bar{T}$ requires:

$$\sum_{t=0}^{\bar{T}} q_t(\bar{p}_t^Q, \bar{T}) = \sum_{t}^{\bar{T}} s_t(B_t(\bar{p}^Q)), \tag{39}$$

where $\bar{p}^Q = (\bar{p}_t^Q)$ is the restricted equilibrium allowance price path. Rewrite (39) as

$$B_{\bar{T}}(\bar{p}^Q) = 0. \tag{40}$$

By conditions (22) and (23),

$$B_{\bar{T}}(p^Q) > 0.$$

From Lemma 3 and (8),

$$\bar{p}_t^Q < p_t^Q, \tag{41}$$

for all $t < \bar{T}$. Using (41),

$$B_t(\bar{p}^Q) < B_t(p^Q), \tag{42}$$

for all $t \leq \bar{T}$. By the mechanics of a quantity mechanism, (42) implies that:

$$s_t(B_t(\bar{p}^Q)) > s_t(B_t(p^Q)), \tag{43}$$

for all $t < \bar{T}$. $\square$

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