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Alternative Approaches to Cost Containment in a Cap-and-Trade System

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RESOURCES FOR THE FUTURE

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Abstract

We compare several emissions reduction instruments, including quantity policies with banking and borrowing, price policies, and hybrid policies (safety valve and price collar), using a dynamic model with stochastic baseline emissions. The instruments are compared under the design goal of obtaining the same expected cumulative emissions across all options. Based on simulation analysis with the model parameterized to values relevant to proposed U.S. climate mitigation policies, we find that restrictions on banking and borrowing, including the provision of interest rates on the borrowings, can severely limit the value of the policy, depending on the regulator-chosen allowance issuance path. Although emissions taxes generally provide the lowest expected abatement costs, a cap-and-trade system combined with either a safety valve or a price collar can be designed to provide expected abatement costs near those of a tax, but with lower emissions variance than a tax. Consistently, a price collar is more cost-effective than a safety valve for a given expected cumulative emissions outcome because it encourages inexpensive abatement when abatement costs decline.

Key Words: cost containment, safety valve, price collar, climate change

JEL Classification Numbers: Q55

Contents

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I. Introduction

Concern about the volatility of allowance prices has long been an element of the U.S. debate about a cap-and-trade scheme for carbon dioxide (CO_2). Even with allowance banking, it is argued, large price swings could result from unanticipated changes in economic activity, weather, fuel prices, or technology development. Price spikes could force expensive mitigation, especially in the short run, whereas sharp price declines might discourage low-cost abatement as well as investment in new technologies. In fact, experience with previous environmental markets indicates considerable price volatility. For climate change, the issue may be especially salient, as efforts to control emissions may prove to be costly, eventually amounting to several percent of gross domestic product.

Analysis linking uncertainty to instrument choice has its roots in the work of Weitzman (1974). This framework has been extended by Pizer (1999), Hoel and Karp (2001, 2002), and Newell and Pizer (2003) to consider stock externalities (pollutants) accumulating over time. They find that price policies tend to produce larger net benefits than quantity-based regulations. Yet, with respect to climate change mitigation, political economy issues have driven the focus on quantity controls, especially cap and trade, albeit with the inclusion of provisions to limit price volatility. In a recent study, Fell, et al. (2008) examined such provisions in the context of a stochastic dynamic framework, focusing on cost savings derived from allowance banking. Fell, et al. found that banking can considerably reduce the costs of a quantity-based regulation, with savings depending on the correlation of abatement cost shocks and growth of abatement requirements and other features. However, in all instances examined, Fell, et al. still found that price policies provide the lowest expected abatement cost by a substantial margin.

It is also possible to combine quantity and price instruments—so-called hybrid policies—as originally discussed in Roberts and Spence (1976) and Weitzman (1978). In terms of climate change policy, papers by Kopp, et al. (1997), McKibbin and Wilcoxen (1997), Pizer (2002), and

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Newell, et al. (2005) examine how cap-and-trade mechanisms can be reconciled to more efficient price policies via the introduction of a safety valve or trigger price that effectively caps allowance (permit) prices by providing an unlimited supply of additional allowances at predetermined prices. Reflecting concerns about the environmental integrity of this approach, Murray, et al. (2008) introduced the notion of a quantitative restriction on the number of allowances that could be issued. Specifically, they advance a form of long-term or reserve borrowing with specified limits and payback to include interest. Both the safety valve and reserve borrowing approaches, along with allowance banking and borrowing provisions, have been incorporated into various legislative proposals for a U.S. cap-and-trade system.

Most recently, papers by Philibert (2008) and Burtraw, et al. (2009) have advanced the idea of a symmetric safety valve, also known as a price collar, which would limit price volatility on both the upside and the downside. The upside trigger would be identical to the original safety valve. In the context of a system that involved considerable auctioning of allowances, the downside would be governed by a reserve auction price. If low prices prevailed for several years, the reserve auction price mechanism might be supplemented by reduced allocations in later years. To ensure that the price collar did not also introduce further uncertainty about future prices, the rules of the road would be established in advance for relatively long time periods. Interestingly, based on a retrospective analysis of Title IV of the 1990 Clean Air Act Amendments, Burtraw et al. calculate that a price collar reflecting legislative intent would have improved economic welfare considerably, on the order of $1.5 to $8.25 billion per year since 1995 (in 2004 dollars). Similarly, using a four period model developed by the International Energy Agency to assess the goal of halving global energy-related CO_2 emissions by 2050, Philibert (2008) finds a collar can meet the emissions reduction objective more cost effectively than emissions standards alone or emissions standards with a price cap.

Despite the range of cost containment approaches advanced to reduce price volatility in a domestic CO_2 cap-and-trade system, questions remain about their *relative* performance, both in terms of environmental performance (emissions reduced) and costs. In the present paper, we attempt to fill that void by developing an analytical framework for comparing the costs of alternative mechanisms, including hybrid versions of the alternatives, *holding constant the expected environmental outcomes.* Specifically, we present a stochastic dynamic representative firm model in which the firm chooses emissions paths under various regulatory regimes in an effort to minimize abatement costs, à la Fell et al. The policy is not updated after it is implemented. We break from Fell et al. in that we consider a finite time horizon model, which allows for greater flexibility in modeling the issuance path for emissions allowances. By performing Monte Carlo simulations, we estimate the means and distributions of both the expected cumulative emissions and the costs. This paper differs from the price collar analyses of Burtraw, et al. (2009) and Philibert (2008) in two key ways. First, both Burtraw, et al. (2009) and Philibert (2008) use a deterministic model where parameter values vary to approximate a world of uncertainty, whereas we explicitly model firms' efforts to minimize abatement costs in the face of uncertain future emissions and abatement costs. Second, unlike the previous analyses, we couple the hybrid mechanisms with allowance banking and borrowing provisions. The inclusion of banking and borrowing provisions alters the firm's dynamic cost minimization problem by linking abatement decisions across time. Specific policies considered include: cap-and-trade without banking/borrowing, cap-and-trade with unlimited banking/borrowing, cap-and-trade with restricted banking/borrowing, cap-and-trade with price collars and restricted banking/borrowing, cap-and-trade with a safety valve and restricted banking/borrowing, and a tax policy. For comparison purposes, the analysis is keyed to the basic parameters contained in S. 1766, the Bingaman-Specter legislation (U.S. Congress 2007c). It includes CO_2 and other covered gases/sources.

Overall, we find that the restrictions imposed on banking and borrowing in current proposals can be costly. Adding a safety valve or price collar to the reserve borrowing proposal can further reduce costs. In fact, based on our modeling, we find that a price collar can achieve costs almost as low as a tax, albeit with less emissions variation than a tax. We also find that price collar mechanisms outperform their safety valve counterparts in terms of expected abatement costs at the same level of expected cumulative emissions, while retaining similar upper emissions bounds.

The organization of the paper is as follows. In section II, we outline the basic model. In section III, we review the solution algorithm used and describe the parameterization of the model. Section IV discusses the implication of allowance borrowing restrictions. Section V presents the policy comparisons under different assumed allowance issuance paths and price mechanism derivations. Concluding remarks are made in section VI.

II. The Model

The model presented here is a representative firm model. We do not consider internal trading among market participants.[1] We start with a firm that has convex abatement costs of the form

$$\frac{c_t}{2}\left(\bar{q}_t + \theta_t - q_t\right)^2 \qquad (1)$$

where $\bar{q}_t$ represents the expected baseline emissions (average cost-minimizing emissions) at time t, θ_t is the shock to baseline emissions and q_t is the firm's emissions choice at time t. Given the quadratic form, c_t represents the slope of the marginal cost function ($c_t > 0$). We allow the shocks to be correlated across time by representing θ_t as a deterministic function of an order one autoregressive process: $\theta_t = \tilde{\theta}_t(1+g_\theta)^{t-1}$, $\tilde{\theta}_t = \rho\tilde{\theta}_{t-1} + \varepsilon_t$, with $|\rho| \le 1$ and $\varepsilon_t \sim N(0, \sigma^2)$. Additionally, we assume that both c_t and $\bar{q}_t$ follow known deterministic paths: $c_t = c_0(1+g_c)^{t-1}$, $\bar{q}_t = \bar{q}_0(1+g_{\bar{q}})^{t-1}$, with $g_c < 0$ and $g_{\bar{q}} > 0$.

Because the focus of this paper is CO_2 regulation, we assume that emissions accumulate in the atmosphere as a nearly pure stock pollutant. By considering a stock pollutant for which a significant damage threshold is not near, the regulator focuses on cumulative emissions over the regulatory period rather than the emissions time path. We also avoid formalizing a specific benefits function for the reduction of the stock pollutant and instead operate under the assumption that the regulator implements policy to obtain a predetermined cumulative emissions target.

In the case of a cap-and-trade program without banking and borrowing, the firm's choice of emissions in each period is simply equal to the period-specific issuance of allowances, y_t. However, when banking and borrowing are introduced, solving for the firm's emissions path problem becomes more difficult because it is possible that $q_t \neq y_t$ as the firm chooses bank/borrow levels to reallocate allowances across time. The firm's optimization problem with banking and borrowing is given as

$$\max_{q_t} \sum_{t=0}^{T} -\beta^t \frac{c_t}{2}\left(\bar{q}_t + \theta_t - q_t\right)^2 \qquad (2)$$

[1] As shown in Rubin (1996), in a dyanmic model with banking and interfirm allowance trading,the market equilibrium of a multi-firm analysis results in the minimization of total costs. This suggests that we can model the problem using a single representative firm.

subject to

$$\begin{aligned} &B_{t+1} = R_t\left(B_t + y_t - q_t\right) \\ &B_{\min,t+1} \le B_{t+1} \le B_{\max,t+1} \\ &B_{T+1} \ge 0 \end{aligned} \tag{3}$$

Equation (2) represents the firm's objective to minimize the net present value (NPV) of abatement costs (equivalent to maximizing negative NPV of abatement costs), where β is the firm's discount factor. The first constraint given in (3) defines the banking dynamics. This constraint simply states that next period's bank level (B_{t+1}) is equal to this period's bank level (B_t) plus the difference between the allowances issued this period (y_t) and this period's actual emissions (q_t), multiplied by a regulator-imposed interest rate (R_t).[2] Note that R_t, also referred to as the intertemporal trading ratio, has a time subscript. The time subscript is imposed because, as in proposed legislation, the interest rate may vary depending on whether the firm banks or borrows (e.g., U.S. Congress 2007b). More specifically we consider R_t of the form

$$R_t = \begin{cases} R_{pos} & \text{if}\left(B_t + y_t - q_t\right) \ge 0 \\ R_{neg} & \text{otherwise} \end{cases} \tag{4}$$

Also consistent with proposed legislation, the second constraint in (3) allows for the regulator to set period limitations on banking and/or borrowing. The final constraint of (3) puts a terminal condition on the problem, which states that the firm may not have any outstanding borrowed allowances at the completion of the regulatory period.

Given the above problem specification, the corresponding Bellman equation can be written as

$$V_t\left(B_t,\theta_t\right) = \max_{q_t}\left\{-\frac{c_t}{2}\left(\overline{q}_t + \theta_t - q_t\right)^2 + \beta E_t\left[V_{t+1}\left(B_{t+1},\theta_{t+1}\right) \mid B_t,\theta_t\right]\right\} \tag{5}$$

subject to (3). We have defined $V_t(B_t,\theta_t)$ recursively as the expected NPV of abatement costs in period t, conditional on the current bank level B_t and baseline emissions shock θ_t and assuming optimal behavior in every future period. Therefore, by solving for $V_0(B_0, \theta_0)$, we can solve for the expected discounted abatement cost of a regulatory policy given an initial bank level/shock

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[2] For the purpose of this paper, the term *bank levels* and variable B_t can encompass both banking states ($B_t \ge 0$) and borrowing states ($B_t < 0$).

condition. Unfortunately, solving for $V_0(B_0, \theta_0)$ is not a straightforward task, as described in more detail in the next section.

The price collar case we consider is a fairly straightforward extension of the problem above. Specifically, the price collar simply acts as price floor and price ceiling for emissions allowance prices, where the price of emissions at time *t*, P_t, is given as the marginal cost of abatement, $P_t = MC_t\left(q_t\right) = c_t\left(\overline{q}_t + \theta_t - q_t\right)$. When the price ceiling is in effect, we assume that the regulator offers a sale of an unlimited number of allowances at the ceiling price P_t^c. When the price floor is triggered, we assume that the regulator buys allowances at the price floor value P_t^f.[3] Thus, the firm's problem now has the additional constraint $P_t^f < P_t < P_t^c$.

When the price of allowances lies between the ceiling and floor prices, the optimization problem is the same as that described above. When the price ceiling is triggered, the firm essentially acts as if an emissions tax is imposed and emits up to the point where $MC(q_t) = P_t^c$, purchasing additional allowances beyond the issued y_t level to cover its emissions q_t. However, in the case where banking is allowed, the firm may purchase more allowances than needed to cover the difference between q_t and y_t in an effort to increase its bank level. Denoting q_t^p as the quantity of allowances purchased when a price ceiling is triggered, the optimization problem during a period when the price ceiling is in effect can be written as

$$V_t\left(B_t, \theta_t\right) = \max_{q_t}\left\{-\frac{c_t}{2}\left(\overline{q}_t + \theta_t - q_t\right)^2 - P_t^c q_t^p + \beta E_t\left[V_{t+1}\left(B_{t+1}, \theta_{t+1}\right) \mid B_t, \theta_t\right]\right\} \qquad (6)$$

subject to an altered bank dynamics equation, $B_{t+1} = R_t\left(B_t + y_t + q_t^p - q_t\right)$. Differentiating (6) with respect to q_t^p leads to the allowance purchasing rule

$$P_t^c = R_t \beta E_t\left[\frac{\partial V_{t+1}(B_{t+1}, \theta_{t+1})}{\partial B_{t+1}} \mid B_t, \theta_t\right] \qquad (7)$$

That is, the firm will purchase allowances up to the point where the expected discounted marginal value of a unit of banked allowances is equal to the price ceiling.

With a price floor in effect, again the firm will act as though a tax is imposed and emit to the point where $MC(q_t) = P_t^f$. The firm then must decide how many of the excess allowances it

[3] Baumol and Oates (1988) argue that subsidizing emissions reductions in a competitive industry can lead to decreased output at the firm level, but increased output at the industry level and can also lead to higher emissions. We do not consider such distortion in this analysis.

will sell back to the regulator and how many it will contribute to the bank, assuming banking is allowed. Denoting q_t^s as the allowances the firm sells back to the regulator, the firm's optimization problem in a period with the price floor triggered can be written as

$$V_t\left(B_t,\theta_t\right)=\max_{q_t}\left\{-\frac{c_t}{2}\left(\overline{q}_t+\theta_t-q_t\right)^2+P_t^f q_t^s+\beta E_t\left[V_{t+1}\left(B_{t+1},\theta_{t+1}\right)\mid B_t,\theta_t\right]\right\} \tag{8}$$

subject to the altered bank dynamics equation $B_{t+1}=R_t\left(B_t+y_t-q_t^s-q_t\right)$ and the limit on allowance sales $0<q_t^s\le(y_t-q_t)$. Assuming the q_t^s limit is not binding, differentiating (8) with respect to q_t^s yields the following allowance sales rule

$$P_t^f=R_t\beta E_t\left[\frac{\partial V_{t+1}(B_{t+1},\theta_{t+1})}{\partial B_{t+1}}\mid B_t,\theta_t\right] \tag{9}$$

Similar to (7), (9) states that the firm will sell allowances back to the regulator until the point at which the discounted expected marginal value of banking an allowance equals the price floor. Assuming that sales back to the regulator can happen, the floor acts as a mechanism to remove allowances from the system and, therefore, counteracts the allowance, creating the properties of the price ceiling.

For the purpose of this paper, a safety valve is equivalent to a collar without a price floor. Thus, if the price ceiling is set at a level where it may be binding, cumulative emissions will exceed those of a cap-and-trade system if the allowance issuance path is the same for both systems. To reach the same expected cumulative emissions target under a safety valve as that of a cap-and-trade system, the regulator must issue fewer allowances.

For a tax policy, we assume that the regulator sets the tax to achieve an ex-ante expected emissions path y_t. Knowing that the firm will equate $MC(q_t)$ to the tax level, the regulator sets the tax in each period equal to

$$tax_t=E\left[c_t\left(\overline{q}_t+\theta_t-y_t\right)\right]=c_t\left(\overline{q}_t-y_t\right) \tag{10}$$

By setting $MC(q_t) = tax_t$, we get the firm's emissions level at each time period $q_t=y_t+\theta_t$. Substituting this result back into (2), we calculate the firm's NPV of abatement cost under a tax policy as

$$\sum_{t=0}^{T}\beta^t\frac{c_t}{2}\left(\overline{q}_t-y_t\right) \tag{11}$$

From (11) we see that, regardless of the realized shocks to baseline emissions, the tax policy leads to the same NPV of abatement costs for a given regulator-proposed emissions path target, y_t.

The above discussion outlines the general model properties of the policies we examine in this paper. The goal is to compare these policies on the basis of expected NPV of abatement costs, holding constant the expected cumulative emissions. This requires solving for $V_0(B_0, \theta_0)$ for each policy. Unfortunately, given the uncertainty in the model, closed-form solutions to the recursive Bellman equations do not exist. We proceed by solving these problems through numerical methods as described in the next section.

III. Numerical Analysis

To solve a numerical approximation to the problems described above, we first discretize θ_t and B_t. We consider 201 possible θ_t values and 201 possible B_t values at each time period. To discretize θ_t, we first discretize $\tilde{\theta}_t$ by creating 201 evenly spaced values of $\tilde{\theta}_t$ on the interval from –5 to 5 standard deviations (based on σ^2) away from the zero mean, and then multiply each discrete value by $(1 + g_\theta)^{t-1}$ to get the θ_t. Given the distribution of ε_t and the AR(1) process of $\tilde{\theta}_t$, a transition probability matrix for θ_t to θ_{t+1} can also be constructed. B_t is discretized by creating 201 evenly spaced values of B_t on the interval from $B_{\min,t}$ to $B_{\max,t}$. In addition, by discretizing B_t for all t and by forming a predefined y_t path, q_t is, in effect, discretized for each time period given the bank dynamic equation in (3).

Because the cost minimization problem is set up as a finite time horizon problem, we use a backward recursion solution algorithm to solve the value function $V_t(B_t, \theta_t)$ in each time period. This solution algorithm begins by solving $V_T(B_T, \theta_T)$. Under the assumption that the terminal period constraint is binding ($B_{T+1} = 0$), it is straightforward to solve q_T and the resulting abatement costs for each (B_T, θ_T) state, $V_T(B_T, \theta_T)$, given that $B_{T+1} = 0$. With $V_T(B_T, \theta_T)$ and the transition probability matrix for θ_{T-1} to θ_T, one can solve for the expected value function, $E\left[V_T\left(B_T, \theta_T \mid B_T, \theta_{T-1}\right)\right]$. Given $E\left[V_T\left(B_T, \theta_T \mid B_{T-1}, \theta_{T-1}\right)\right]$, a q^*_{T-1}, and the resulting V_{T-1}, can be solved for as the value of q_{T-1} that maximizes (5). For the cases of price collars and safety valves, if a resulting optimal q^*_{T-1} triggers a price ceiling (floor), then $\hat{q}_{T-1}$ will be such that $MC_T(\hat{q}_{T-1}) = P^c_{T-1}\left(MC_T(\hat{q}_{T-1}) = P^f_{T-1}\right)$, and $q^p_{T-1}\left(q^b_{T-1}\right)$ will be chosen to maximize (7) ((8)). The variable q^*_{T-1} is then defined as $q^*_{T-1} = \hat{q}_{T-1} + q^p_{T-1}$ when a price ceiling is in effect and $q^*_{T-1} = \hat{q}_{T-1} + q^s_{T-1}$ when a price floor is in effect. This recursive procedure of solving V_{t-1} given V_t, including adjustments for possible price floors and ceilings, is repeated until $t = 0$. The end results of this recursion are $T + 1$ $V_t(B_t, \theta_t)$ value matrices that define the expected NPV of abatement cost at each possible (B_t, θ_t) combination for each time period 0 to T, as well as $T + 1$

$q_t^*(B_t, \theta_t)$ matrices that define the optimal emissions level for each possible (B_t, θ_t) combination at each time period.

With the given condition (B_0, θ_0), $V_0(B_0, \theta_0)$ gives the expected NPV of abatement cost for the policy in question. However, with safety valve and price collar policies considered, finding expected cumulative emissions is not as straightforward. We therefore use the optimal emissions choice matrices $q_t^*(B_t, \theta_t)$ and the banking dynamic equations in Monte Carlo simulations where we first generate θ_t series then derive firm-optimal emissions and bank level paths. Our simulation results are based on 2,500 simulated paths for each policy considered.[4]

Values used in our numerical analyses are based on those relevant to the U.S. climate policy debate, with emissions targets loosely parameterized to S.1766 - Low Carbon Economy Act of 2007 (U.S. Congress 2007c). We consider a time horizon of 39 periods ($t = 0$ to $t = 38$), corresponding to a policy running from 2012 to 2050. To calculate baseline emissions, we first sum expected emissions from greenhouse gases (GHGs) covered under S.1766—CO_2 emissions from fossil fuels based on EIA's Annual Energy Outlook 2009[5] (EIA 2008a), and nitrous oxide emissions from adipic and nitric acid production (EIA 2008a). Projections of these emissions are given from 2012 to 2030. For simplicity, we assume that baseline emissions grow at a constant rate from 2012 to 2050 (i.e., $\overline{q}_t = \overline{q}_0(1+g_{\overline{q}})^{t-1}$). We use the calculated 2012 baseline emissions level as $\overline{q}_0$ and calculate $g_{\overline{q}}$ using the calculated 2030 baseline emissions value.[6]

S.1766 calls for emissions to be reduced to 2006 baseline emissions levels by 2020, to 1990 baseline emissions levels by 2030, and at least 60 percent below 2006 baseline emissions levels by 2050. The bill also outlines an annual emissions allowance issuance path for 2012 to 2030. However, in light of the recent economic downturn, the allowance issuance path as written would likely require little or no early-period emissions cuts. Thus, we alter this emissions path by assuming that the allowance issuance declines at a constant rate from 2012 to 2050 (i.e., $y_t = y_0(1 + g_y)$). To solve for g_y we assume that y_0 is equal to expected 2010 baseline emissions (6.032

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[4] Reported emissions values resulting from simulation exercises take into account that, for periods with a price ceiling or price floor in effect, the actual emissions level is $\hat{q}_t$ not q_t^*.

[5] See: http://www.eia.doe.gov/oiaf/aeo/aeoref_tab.html, flourinated gases emissions.

[6] The resulting baseline emissions path obtained from this process closely follows, but is slightly below, the expected baseline emissions path for covered emissions according to EIA's analysis of S. 2191 (EIA 2008b). This baseline path is, however, far below the path estimated in EIA (2008a)—a path that does not account for the recent economic downturn.

Gt CO_2) and that the 2030 goal of 1990 baseline emissions levels (4.819 Gt CO_2) is met. We also explore other allowance issuance paths that lead to the same number of cumulative emissions allowances issued over the 39 periods.

We assume that c_0 = \$30/tCO_2, based on estimates used in EPA (2008). The variable c_t is assumed to decline at a constant rate over the time horizon, with $g_c = 0.025$. The discount rate used is $\beta = 0.95$. Based on Newell and Pizer (2003), we set the correlation factor ρ for the baseline emission shocks at 0.8. We set the standard deviation of ε_t, σ, at 1/3 Gt CO_2, roughly five percent of the expected initial baseline emissions. We assume that the shocks grow at the same rate as baseline emissions ($g_\theta = g_{\bar{q}}$), ensuring that the shocks retain their relative importance as baseline emissions increase. For the restricted borrowing cases, we assume that $R_{neg} = 1.08$ and $B_{\min,t} = -0.15y_t$, both values near levels given in S.2191. For all cases with banking, $R_{pos} = 1.0$ and $B_{\max,t}$ is set sufficiently large to ensure that the bank level upper bound is never binding given the other base case parameters (i.e., unlimited banking). These parameter values, along with relevant sources, are summarized in Table 1.

Table 1. Baseline Parameter Values

Description	Parameter	Value	Source
Initial baseline emissions	$\bar{q}_0$	6.158 (Gtons)	2012 value from EIA analysis of S.1766 (using AEO 2009)
Initial allocation	y_0	6.032 (Gtons)	Based on 2010 baseline from EIA (using AEO 2009)
Initial slope of $MC(q_t)$	c_0	\$30/ton	EPA (2008)—Analysis of S.2191
Growth of baseline emissions	$g_{\bar{q}}$	0.0066	EIA—Analysis of S.1766 (using AEO 2009, assuming constant growth)
Decline in slope of MC	g_c	–0.025	
Growth in shock	g_θ	0.0066	
Decline in y_t	g_y	–0.0124	Approximate decline of S.1766
Stnd. error of shock	σ	0.33 (Gtons)	
Corr. of shocks	ρ	0.8	Newell and Pizer (2003)
Interest for borrowing	R_{neg}	1.08	Slightly below S.2191 rate of 10%
Interest for banking	R_{pos}	1.0	Value in S.2191, S.1766
Borrowing limit	$B_{\min,t}$	$-0.15y_t$	Based on S.2191 borrowing limit
Discount factor	β	0.95	
Terminal period	T	38	Corresponding to 2012 to 2050

Notes: R_{neg} and $B_{\min,t}$ are used whenever restricted banking/borrowing is referenced. In policy analysis with banking allowed, $B_{\max,t}$ is set such that it is never binding for the parameter values used. g_y is used only for policies with constant-declining emissions paths.

IV. Results with Restrictions on Borrowing

Allowing banking and borrowing gives firms the opportunity to temporally shift abatement requirements. The ability to bank and borrow allowances is useful for the firm for two different, though not necessarily unrelated, reasons. The first reason a firm may bank/borrow, which can happen with or without abatement cost uncertainties, arises when the long-term issuance path designed by the regulator differs from the optimal (cost-minimizing) emissions path of the firm. For instance, if the regulator has imperfect information about the firms' abatement costs or discount rates, the regulator's allowance issuance path will likely deviate from the firm-optimal emissions path. In this case, firms would use banking/borrowing to intertemporally reallocate allowances to match the firm-optimal emissions path. Second, a firm may bank/borrow allowances to smooth out unexpected shocks to abatement costs. Despite the benefits from this additional flexibility, in practice many emissions allowance systems limit, if not prohibit, banking/borrowing.[7]

When the damages from emissions are time path-dependent, the regulator will have an incentive to limit banking/borrowing. The design of optimal intertemporal trading schemes with path-dependent pollutants has been explored by, among others, Rubin (1996), Cronshaw and Kruse (1996), Kling and Rubin (1997), and Yates and Cronshaw (2001). However, most GHGs are stock pollutants, meaning that the damage is a function of the accumulated stock of the pollutant. Given the slow decay rate of many GHGs, particularly CO_2, and assuming that current levels of GHG stocks in the atmosphere are not near a severe damage threshold, the GHG regulator is less concerned with the path of emissions and more focused on the expected accumulation of emissions over the regulatory period. That is, path-dependent damages should not be a primary justification for banking/borrowing restrictions in the context of GHGs.[8]

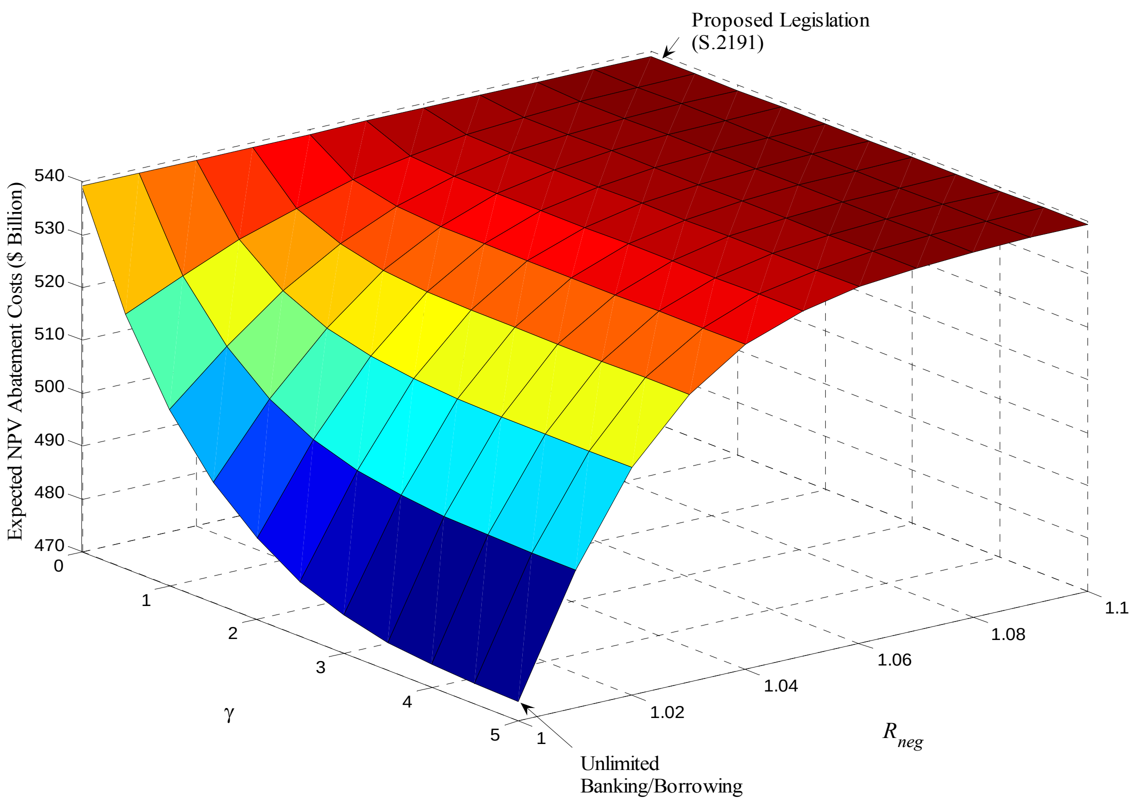
In the case of climate change, political economic concerns seem to be the principal motivation for restricting banking/borrowing and, more specifically, for restricting borrowing. If the regulator fears that excessive borrowing in the early years of the trading program may lead to unacceptably high allowance prices in the future, then the regulator may move to limit borrowing

[7] For instance, in Southern California's RECLAIM trading program, banking and borrowing are effectively prohibited, the E.U.-Emission Trading System and U.S. sulfur dioxide trading program allow banking but prohibit borrowing, and the proposed climate bill S.2191 allows banking and restricted forms of borrowing.

[8] Leiby and Rubin (2001) do consider intertemporal trading ratio restrictions for GHGs, invoking a path dependency based on stock damages, and therefore find some justification for not allowing a one-to-one trading of allowances across time.

in all periods. In proposed U.S. climate change legislation, bills permitting allowance borrowing limit the borrowing quantity in any given period and charge interest on the borrowed allowances (see U.S. Congress 2007a, 2007b, 2008). However, these restrictions on borrowing reduce firms' emissions flexibility and, thus, raise expected program costs. In this section, we attempt to quantify these costs.

Figure 1: Borrowing Restrictions Surface—Constant-Declining Issuance Path



Notes: R_{neg} refers to interest charged on borrowed allowances, γ refers to the fraction of y_t that can be borrowed ($B_{\min,t} = \gamma y_t$).

By solving the dynamic optimization problem given above under the relevant base case parameters, we are able to calculate the expected NPV of abatement costs for different borrowing restriction policies. We focus on the two often-used policy levers for limiting borrowing, quantitative caps and interest to be paid on borrowed allowances. Figure 1 gives a surface plot of the expected NPV of abatement costs given these borrowing limitation policy levers with no price caps or collars and for an allowance issuance path following a constant decline rate. The *y*-axis of Figure 1 presents the borrowing cap as $B_{\min,t} = \gamma y_t$. For instance, $\gamma = 0$

means that borrowing is prohibited, whereas $\gamma = 5$ allows the firm to carry a negative bank level in any period equal to five times the amount of that period's issued allowances.[9] The *x*-axis of Figure 1 represents the interest charged on borrowed allowances. In this case, $R_{neg} = 1$ means that no interest is charged on borrowed allowances, whereas $R_{neg} = 1.10$ means that if an allowance is borrowed at t, then the firm owes 1.10 allowances in $t + 1$, i.e., a 10 percent interest rate. The *z*-axis of Figure 1 represents the expected NPV of abatement costs at $t = 0$ with $B_0 = 0$ and $\theta_0 = 0$ (i.e., $V_0(0, 0)$).

The figure clearly shows that imposing borrowing provisions increases the cost of the cap-and-trade program. Prohibiting borrowing, given the constant-decline allowance path, increases expected abatement costs by about 14 percent compared to the unlimited banking/borrowing case. Furthermore, the figure shows that, for borrowing interest rates greater than approximately six percent, the inclusion of borrowing provides little cost saving versus a complete prohibition on borrowing, regardless of the borrowing level limits. Therefore, borrowing provisions in proposed legislation such as S.2191, which sets $R_{neg} = 1.10$ and $\gamma = 0.15$, provide essentially no expected abatement cost reductions over policies without borrowing.

For the values displayed in Figure 1, banking and borrowing allowances are valuable for dealing with transient, but persistent abatement cost shocks, as well as for reallocating allowances to a firm-optimal emissions path. If the regulator can issue allowances over time in a manner more consistent with the firm's optimal emissions path, given a set cumulative emissions goal, then the intertemporal reallocation of allowances will be used primarily for dealing with the transient cost shocks. Thus, we consider the effects of borrowing restrictions, assuming that the regulator issues allowances according to the ex-ante expected optimal emissions path of the firm for the given cumulative emissions target.[10] A comparison of the ex-ante optimal issuance path and the constant-decline issuance path is given in Figure 2. As shown in this figure, the ex-ante firm-optimal path calls for relatively minor abatement in early periods and significant abatement in later periods. Likewise, for the case with no uncertainty and allowances issued on the constant-decline path, we see that the representative firm would initially bank allowances (firm-optimal path lies below the constant-decline path), then draw down the bank and borrow

[9] For the parameter values used here when $\gamma \approx 5$, $B_{\min,t}$ is never binding.

[10] To solve for this path, we simply solve the dynamic optimization problem (6) with baseline emissions shocks removed and no restrictions on banking and borrowing. The formulation of this path is similar to the "second-best" path discussed in Leiby and Rubin (2001).

allowances in the middle periods of the regulatory term (firm-optimal path is above the constant-decline path), and finally repays the borrowed allowances in the final periods. Though not plotted, it should also be noted that without uncertainty in baseline emissions, the ex-ante firm-optimal allocation path leads allowance prices to follow the well-known Hotelling rule—allowance prices rise at the rate of interest.

Figure 2: Permit Issuing Paths

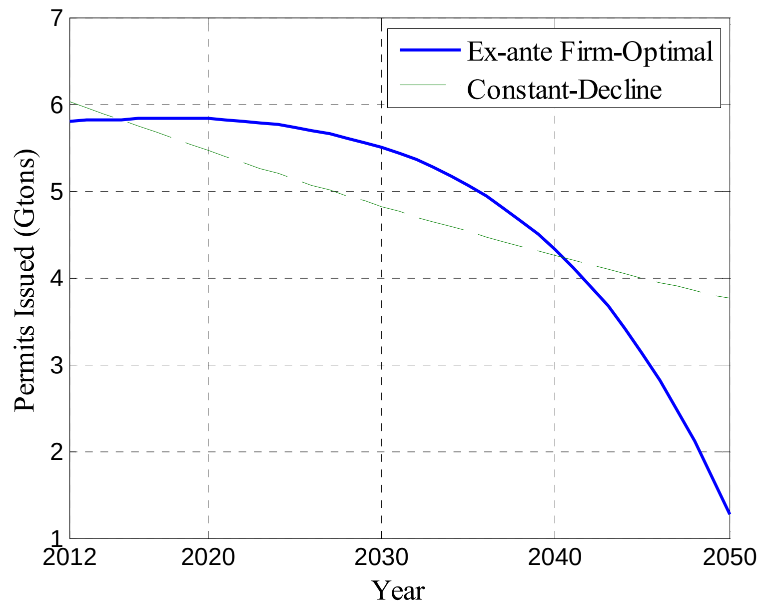
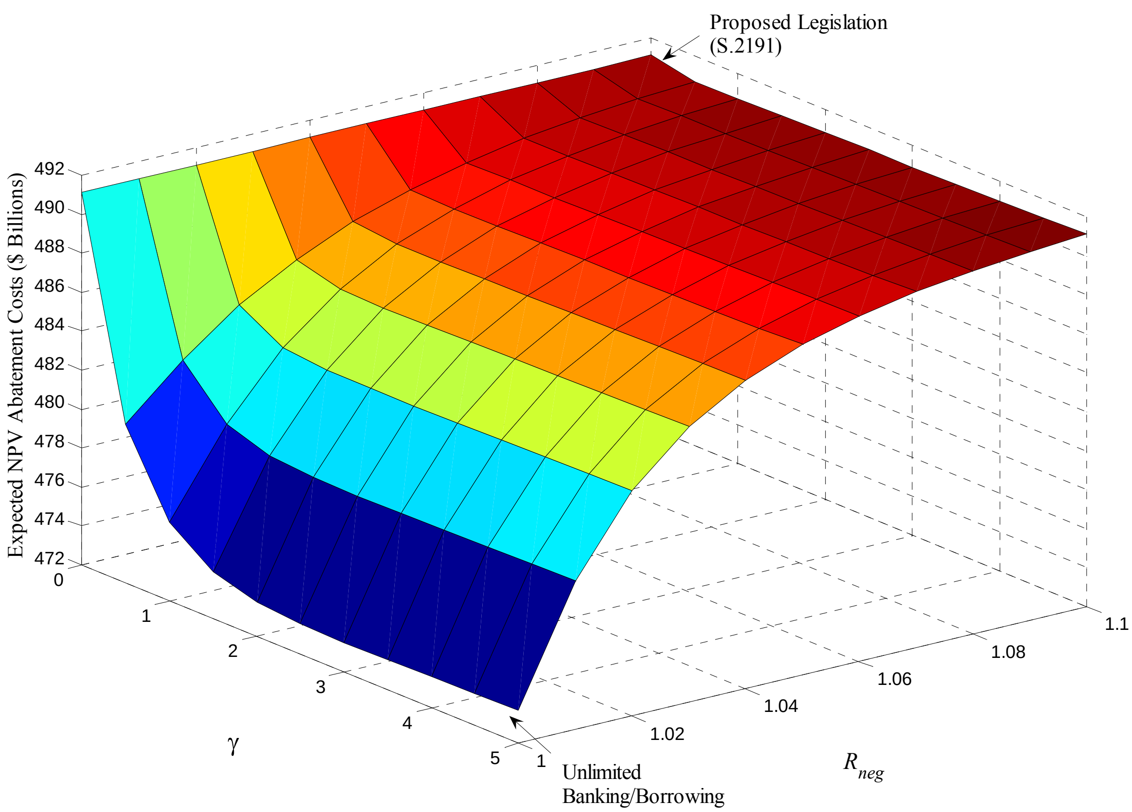


Figure 3 displays the surface plot assuming an ex-ante firm-optimal issuance path. Again, it is evident that borrowing restrictions increase the expected cost of the cap-and-trade program. However, the additional costs associated with these restrictions are far less than those of the constant-decline allowance issuance path case. This is as expected because banking/borrowing is now used primarily to deal with transient, but persistent, cost shocks rather than to make a major modification to the issuance path. With the ex-ante firm-optimal issuance path, prohibiting borrowing increases the expected abatement cost by only four percent compared to the unlimited banking/borrowing case. Again, borrowing interest rates greater than approximately six percent effectively eliminates any expected benefits from including a borrowing provision.

Figure 3: Borrowing Restrictions Surface—Firm-Optimal Issuance Path



Notes: Firm-optimal issuance path refers to the issuance of allowances ex-ante expected optimal emissions path of the firm.

V. Policy Comparison

In this section, we compare abatement costs across various emissions regulation policies, while holding expected cumulative emissions constant across all policies. The general categories of the policies we review are cap-and-trade policies, hybrid policies, and an emissions tax policy. For the cap-and-trade policies, we consider a cap-and-trade system without banking/borrowing; a system with unlimited banking/borrowing; and a system with unlimited banking, but restricted borrowing, where borrowing is restricted by both a borrowing cap and interest charged on borrowed allowances. For hybrid polices, we consider both price collar mechanisms and standard one-sided safety valve mechanisms. We also incorporate unlimited banking and restricted borrowing provisions with the hybrid mechanisms. For these mechanisms, we are focused on abatement costs only. Abatement costs for the hybrid mechanisms do not include the additional cost to firms incurred when they buy allowances at the price ceiling or cost reductions from selling allowances at the price floor, though these cost additions and reductions do appear in the firm's optimization problem. The tax policy we use sets tax rates that are given in (10).

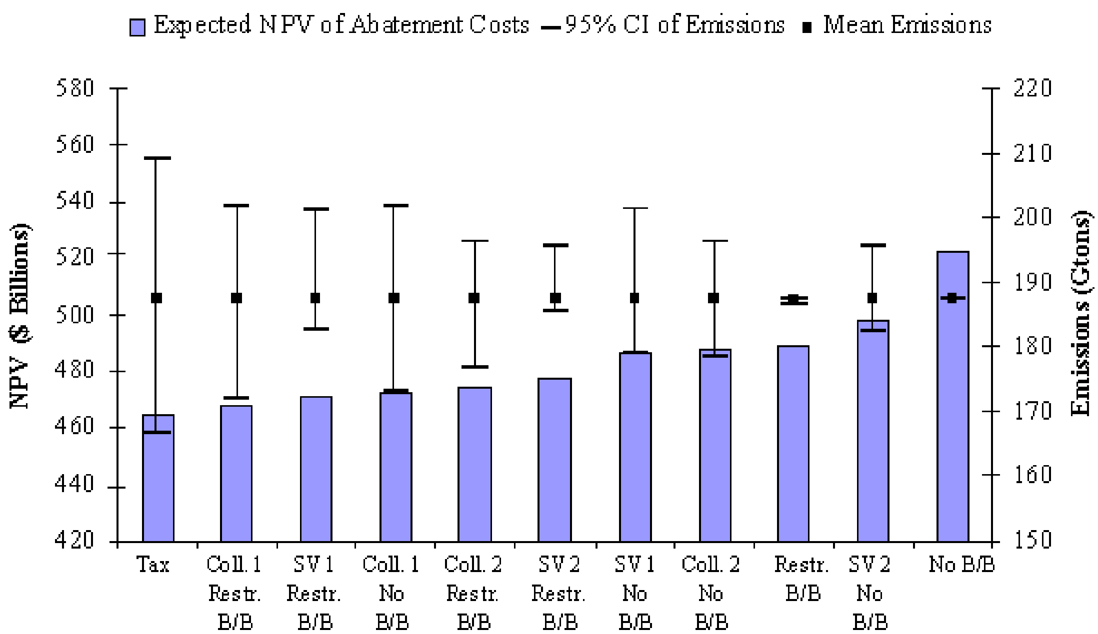
Although the hybrid mechanisms we include here have been discussed in the literature, there is no generally-accepted implementation rule is generally accepted, particularly for the price collar policy. In this study, we consider a *fixed spread* (FS) collar, which maintains a constant spread between P_t^f and P_t^c for all *t*, so $spread_t = P_t^c - P_t^f = X$. Although the spread remains constant over time, the values of P_t^f and P_t^c grow over time. Given this representation, the design questions are, what path should the price collars follow and what should the spread be? We reference the growth of P_t^f and P_t^c to the ex-ante expected allowance price path under a policy with no banking/borrowing, $E_0\left[P_t^y\right] = E_0\left[MC_t(y_t)\right] = c_t\left(\overline{q}_t - y_t\right)$. In the limit, as X approaches zero the collar mechanism becomes a tax policy, and as X becomes very large the collar mechanism effectively becomes a cap-and-trade policy. We choose two intermediate values for the spread, X_1 = \$10 and X_2 = \$20, to differentiate the policy from tax and cap-and-trade policies and also to retain politically realistic spread values. Further, the spread X need not be symmetrically distributed about $E_0[P_t^y]$. That is, if $P_t^c = E_0\left[P_t^y\right] + a$ and $P_t^f = E_0\left[P_t^y\right] - b$ with $a + b = X$, a and b will not necessarily be equal if the goal is to minimize expected NPV of abatement costs while maintaining a constant expected cumulative emissions target. The values of a and b will depend on the particular banking/borrowing provisions adopted. To solve for a and b given X, we used the numerical analysis described above to conduct a grid search over possible values of a and b. The values of a and b used were those that minimized expected abatement costs ($V_0(0, 0)$), while keeping expected cumulative emissions at or below the expected cumulative emissions goal (i.e., the cumulative emissions of the cap-and-trade program). Expected cumulative emissions were taken as the mean of the cumulative emissions from the 2,500 simulations.

To enable a comparison of the safety valve with the price collar mechanism, we consider the safety valve as the one-sided analogue to the collar. That is, the price ceiling for the safety valve is the same price ceiling from the collar mechanism, $P_t^c = E_0\left[P_t^y\right] + a$. Because the safety valve mechanism has no process to remove the excess allowances bought when the ceiling price is triggered, the issuance path of allowances must be more restrictive than either the pure cap-and-trade approach or the collar policy to maintain the expected cumulative emissions goal. The way in which the issuance path is made more restrictive will affect the NPV calculation of abatement costs. From an NPV of abatement cost minimization standpoint, it is more cost-efficient to take emissions allowances from later periods rather than earlier periods. We therefore consider a reduced emissions path of the form

$$y_t^{SV} = y_t - e^{-\phi(T+1-t)} \tag{12}$$

In (12), given a, ϕ is solved as the value that minimizes the expected NPV of abatement costs while keeping expected cumulative emissions at or below the cumulative emissions goal. Expected cumulative emissions were again taken as the mean of the cumulative emissions from the 2,500 simulations.

Figure 4: Policy Comparison—Firm-Optimal Issuance Path



Notes: Coll. 1 refers to the collar with X = \$10. Coll. 2 refers to the collar with X = \$20. SV 1 and SV 2 refer to the policies using the same P_t^c as the Coll. 1 and Coll. 2, respectively. Restr. B/B refers to policies with unlimited banking and restricted borrowing. No B/B refers to policies with no banking or borrowing.

Figure 4 graphically represents a comparison of abatement costs and cumulative emissions for several of the relevant policy alternatives using the firm-optimal allowance issuance path described above (see Table 2 in the appendix for complete results). The expected NPV of abatement costs, referenced on the left-hand side vertical axis, are based on the t = 0 (i.e., 2012) expectation with θ0 = 0 and B0 = 0. Cumulative emissions results, referenced on the right-hand side vertical axis, are based on the 2,500 simulations for each policy. Policies are listed from left to right in order of increasing expected NPV of abatement costs.

As expected under the firm-optimal issuance path, a tax policy represents the lowest expected NPV of abatement across all policies considered for the given cumulative emissions goal. For the price collar mechanisms, we find that the tighter collar (Coll. 1, X = \$10) leads to lower abatement costs than the looser collar (Coll. 2, X = \$20). This is as expected since restricting the spread moves the collar mechanism closer to the tax policy. We also find that adding a banking and restricted borrowing provision to the collar mechanism can further reduce abatement costs compared to the collars without banking/borrowing. This is due to the added flexibility that banking and borrowing allows in dealing with baseline emission shocks. In comparing the collars with their one-sided counterparts, the safety valve policies, we find that the collars have lower expected abatement costs for the given expected cumulative emissions goal. This means that, in this setting, the discounted abatement cost increase of a more restrictive issuance path is greater than the cost increase due to a price floor. Finally, we find that the hybrid mechanisms generally lower expected NPV of abatement costs compared to the straight quantity mechanism (No BB) and compared to the quantity mechanism that allows banking and restricted borrowing (Restr. BB). The exceptions to this are the safety valve policies without banking/borrowing (SV1 No BB, SV2 No BB), both of which had slightly higher expected NPV of abatement costs than the quantity policy that allowed banking and restricted borrowing.

Reviewing cumulative emissions results presented in Figure 4 show that the mean cumulative emissions values are held constant across the policies at 187.4. Though not visibly detectable, the one exception to this rule is for the quantity policy that allows banking and restricted borrowing. The mean cumulative emissions value for this policy lies slightly below the cumulative emissions target of 187.4 because, with $R_{neg} > 1$, any borrowing that occurs effectively takes allowances out of the systems, thereby reducing cumulative emissions.

Looking at the spread of cumulative emissions outcomes, based on the 95 percent confidence intervals, we see that the tax policy leads to the greatest variability in cumulative emissions outcomes. The pure quantity policies, of course, have essentially no variability in cumulative emissions. The hybrid mechanisms reduce the cumulative emissions variability relative to the tax policy, with variability declining as the spread or price ceiling increases. This result is as expected because increasing X or P_c^f brings the hybrid mechanism closer to being a pure quantity policy. In addition, although the collar mechanisms have emissions outcomes that are nearly symmetric about the mean values, the safety valve mechanisms have much more skewed cumulative emissions outcomes. This is because the safety valve mechanisms have no design feature to remove allowances from the system aside from the relatively limited restricted borrowing provisions. This inability to remove allowances, while at the same time allowing for additional allowances to enter the system, skews the distribution toward larger cumulative emissions outcomes.

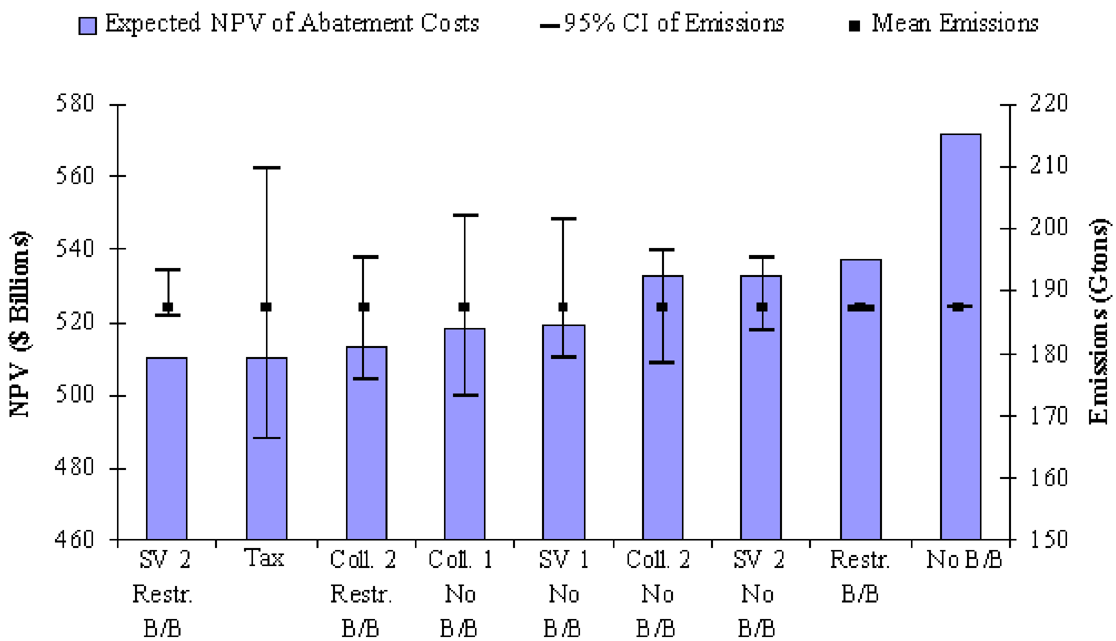
Moving to the constant-declining allowance issuance path, recall that the price mechanisms, tax_t, P_t^c, and P_t^f, are based on an ex-ante expected price of allowances in a cap-and-trade system with no banking and borrowing for the given allowance issuance path, $E_0\left[P_t^y\right]$. Therefore, the constant-declining allowance issuance path will lead to price mechanisms that do not rise at the rate of interest. In fact, $E_0\left[P_t^y\right]$ rises at a rate greater than the rate of interest at the beginning of the regulatory term and then slows toward the end of this term. Because $E_0\left[P_t^y\right]$ grows faster than the rate of interest in the early period, arbitrage opportunities can exist under a collar mechanism with banking if the spread is sufficiently narrow. That is, firms can buy and bank extra allowances at the ceiling price, then turn around and sell these allowances back to the regulator at floor prices in later periods. This can lead to cumulative emissions greater than the sum of issued allowances (i.e., the cumulative emissions target is exceeded) if the realized baseline emission shocks are such that the arbitrage opportunity cannot be fully met. Similarly, because $E_0\left[P_t^y\right]$ starts out lower in the constant-declining issuance path than in the firm-optimal issuance path, if the price ceiling for a safety valve mechanism is set too low, excessive banking will occur in early periods leading to cumulative emissions outcomes greater than the target. This cannot always be corrected with a stricter issuance path because the stricter issuance path further increases the incentive to excessively bank in early periods.

For our numerical analysis, with the constant-declining allowance issuance path it is not possible for expected cumulative emissions to meet the cumulative emissions target for the hybrid policy price collar mechanism where X = \$10 and banking/restricted borrowing is allowed. This policy and its safety valve analogue are therefore dropped in our policy comparison analysis for the constant-declining emissions path.

Figure 5 gives a similar abatement cost and cumulative emissions comparison as in Figure 4, but the policies are based on the constant-declining allowance issuance path. Again, the policies are given from left to right in order of increasing expected NPV of abatement costs. The hybrid mechanisms with banking and restricted borrowing are nearly equal to the tax, and the safety valve mechanism has a slightly lower expected NPV of abatement costs (see Table 3 in the appendix for full details of values underlying Figure 5).[11] This is because the price ceiling allows for additional banking early in the regulatory term, resulting in an emissions path closer to the firm-optimal path. When banking and borrowing are not allowed, the price collars have nearly the same expected NPV of abatement costs as their safety valve analogues, with costs increasing as the spread or P_t^c increases. This suggests that for the constant-decline path there is little abatement cost trade-off between the addition of a price floor and a more restrictive allowance issuance path when banking/borrowing is not allowed. Finally, as has been shown in other related studies (e.g., Cronshaw and Kruse 1996 and Rubin 1996), we see that including banking/borrowing, even if the borrowing is restricted, can lead to considerable discounted abatement cost savings compared to a quantity policy without intertemporal trading when the allowance issuance path varies significantly from the firm-optimal path.

[11] Both safety valve and price collar mechanisms with *a* and *b* values other than what is shown here can meet the cumulative emissions target and have expected NPV of abatement costs lower than that of the tax policy.

Figure 5: Policy Comparison—Constant-Declining Issuance Path*



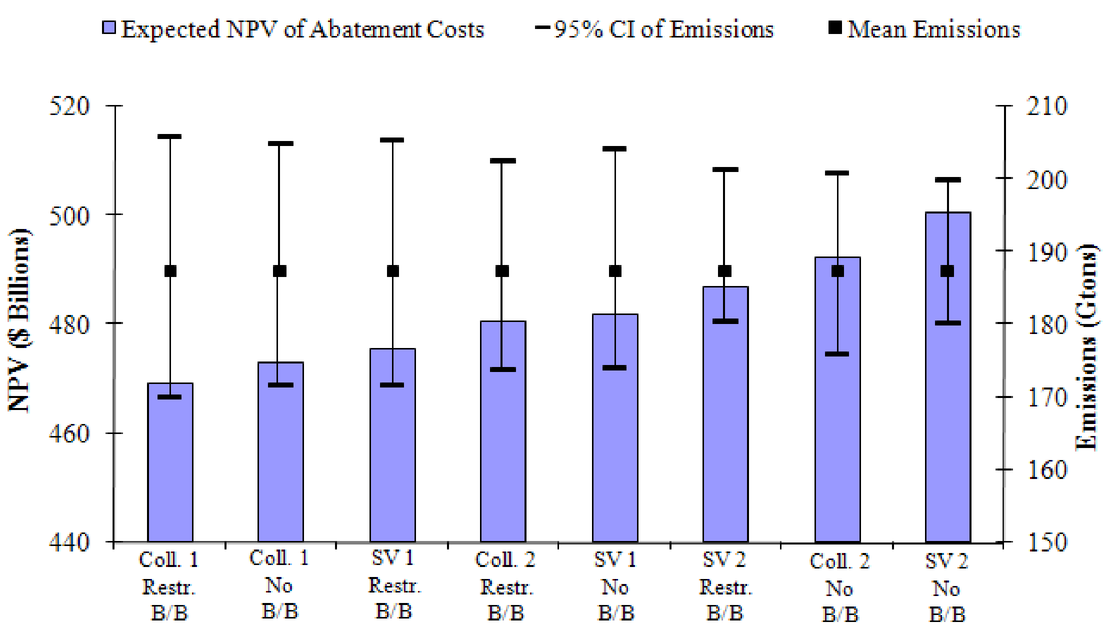
*Notes: Coll. 1 refers to the collar with X = \$10. Coll. 2 refers to the collar with X = \$20. SV 1 and SV 2 refer to the policies using the same P_t^c as the Coll. 1 and Coll. 2, respectively. Restr. B/B refers to policies with unlimited banking and restricted borrowing. No B/B refers to policies with no banking or borrowing.

Finally, we evaluate the hybrid mechanisms under a combination of the scenarios described above. For this "mixed" case, allowances are issued on the constant-decline issuance path, but P_t^c and P_t^f are designed such that they grow at the firm's rate of interest, as they did in our "firm-optimal issuance path" analysis. This mixed case is not without real-world context. For example, as noted, the allowance issuance path given in S.1766 more closely resembles our constant-decline path than our ex-ante firm-optimal path, but the price ceiling provision in that proposed legislation grows at a rate of five percent annually.

Figure 6 presents a graphical comparison of the hybrid mechanisms' expected NPV of abatement costs and cumulative emissions outcomes for the mixed case described above (detailed values given in Table 4 in the appendix). Again, the collar mechanisms provide lower expected NPV of abatement costs than their safety valve counterparts. However, all hybrid mechanisms analyzed here had lower expected NPV of abatement costs than a tax policy designed to achieve an emissions path equal to the constant-decline allowance issuance path. The hybrid mechanisms also provide similar upper limits on the 95 percent confidence intervals of cumulative emissions, suggesting little trade-off of the two mechanisms based on environmental standards.

In comparing the results of the hybrid mechanism under the "mixed" scenario case to the those presented in the constant-decline issuance path scenario, we see that having the price mechanisms referenced to an expected emissions price that rises at the rate of interest, instead of being based on $E_0\left[P_t^y\right]$ of the constant-decline issuance path reduces expected abatement costs considerably. This is because when P_t^c is based on the $E_0\left[P_t^y\right]$ of the constant-decline issuance path, it is generally higher than the P_t^c based on the firm-optimal price path and therefore not useful in protecting against high abatement cost periods. In the case where P_t^c is based on an expected price rising at the rate of interest, it is following the firm's optimal price path and therefore more useful in reducing high-cost periods. However, this cost reduction is coupled with a greater variance in cumulative emissions outcome. Again this is because P_t^c based on the ex-ante firm-optimal price path is relevant for more subperiods in the regulatory term when it is rising at the rate of interest compared to when it is based on $E_0\left[P_t^y\right]$.

Figure 6: Policy Comparison—Constant-Declining Issuance Path, Firm-Optimal Price Mechanisms*



*Notes: P_t^c and P_t^f both increase over time at a rate equal to the firm's interest rate. The permit issuance path declines at a constant rate g_y. Coll. 1 refers to the collar with X = \$10. Coll. 2 refers to the collar with X = \$20. SV 1 and SV 2 refer to the policies using the same P_t^c as the Coll. 1 and Coll. 2, respectively. Restr. B/B refers to policies with unlimited banking and restricted borrowing. No B/B refers to policies with no banking or borrowing.

VI. Conclusion

As the U.S. moves forward with a cap-and-trade policy for CO_2 emissions, concerns persist over the potential volatility of regulatory costs. Several mechanisms have been suggested to protect against untenably high volatility in compliance costs. In this study, we compare several of these mechanisms, including quantity-based policies with banking and borrowing, price policies, and hybrid policies (safety valve and price collar), using a dynamic model with stochastic baseline emissions. Unlike most other instrument comparison studies, we do not specify an emissions damage function; rather, we compare mechanisms under the design goal of obtaining the same expected cumulative emissions across all policies.

A number of policy-relevant observations emerge from this analysis. First, it is clear that allowance borrowing can lower costs, significantly so when allowances are issued such that they decline at a constant rate—as in pending legislation—rather than on the basis of an ex-ante firm-optimal emissions path. Restrictions on borrowing, including requirements to pay interest, can be quite costly. In our modeling, interest rates above six percent per annum negate virtually all the gains from borrowing.

Second, the inclusion of a safety valve or a price collar (symmetric safety valve) can significantly reduce costs compared to pure quantity-based instruments, almost to the levels of a pure tax. At the same time, the safety valve and price collar both result in less cumulative emissions variability than a pure tax. In our simulations, we find that price collars and safety valves can reduce expected abatement costs by as much as 18 and 17 percent, respectively, relative to a cap-and-trade system with no banking and borrowing. These cost savings are reduced, however, if the allowance issuance path more closely resembles the firm-optimal emissions path and/or unlimited banking and borrowing of allowances is permitted. In terms of cumulative emissions, we find that the upper end of the 95 percent confidence interval for cumulative emissions of a tax policy is 3 to 7 percent higher than that of the price collar and safety valve scenarios examined here.

Third, a price collar is always more cost-effective than a safety valve for a given expected cumulative emissions outcome because it encourages inexpensive abatement when allowance prices decline. At the same time, the upper end of cumulative emissions outcomes for the two hybrid mechanisms is quite similar. Also, though not the focus of this study, a price collar may encourage greater investment in new technologies by reducing concerns about a price collapse.

Fourth, even with a constant-declining allowance issuance path, there are efficiency gains from having the trigger prices in either a safety valve or a price collar based on a price path that rises at the rate of interest, consistent with the Hotelling rule. This is because price ceilings based on the firm-optimal price path that rises at the rate of interest are lower during early periods than those based on the expected price path from the constant-decline issuance path, allowing for a greater build up of the bank which helps with the high abatement costs in later periods.

Although not fully examined at this time, several other observations emerge from the analysis. First, although we present hybrid instruments designed to produce expected cumulative emissions at our pre-specified target, the cumulative emissions results are quite sensitive to the parameters employed in the hybrid mechanisms. That is, altering the distribution of the price collar about the ex-ante expected price can lead to significantly different expected emissions and abatement cost results. Likewise, for a given trigger price on the safety valve mechanism, both cumulative emissions and abatement costs are quite sensitive to the allowance issuance path. This suggests that uncertainty about assumed parameters in our model could result in a policy design wherein expected cumulative emissions deviate from the regulator's cumulative emissions target. This is true for both hybrid policies and an emissions tax.

Additionally, the price floor mechanism examined here is one in which the regulator buys back allowances when the floor is triggered. Operationally, this floor could also work by setting a reserve price in allowance auctions. In such a framework, our model would have to be amended to include the firm's selection of not only the state-dependent emissions level, $q_t(B_t, \theta_t)$, but also an auction purchase quantity. Since, in an auction setting, the firm is essentially choosing its allocation each period, this raises another modeling issue: is the baseline emissions shock observed before or after the auction purchase is decided? Although we leave this issue for future research, the link between auction frequency and uncertainty is clear.

Finally, we emphasize a key point underlying this entire analysis: despite the obvious appeal of the metric expected cumulative emissions, for comparing the performance of various instruments used to control a stock pollutant like CO_2, this may not be a universally accepted measure. Depending on the findings of climate scientists, the possibility that cumulative emissions outcomes exceed some pre-specified target in a particular regulatory period may be unacceptable, despite the potentially equal probability that this measure of emissions falls below that target. Furthermore, information about unacceptably high cumulative emissions outcomes may vary over time as new information about global climate systems comes to light. Regardless of these potential limiting factors, the analysis clearly indicates that, in choosing among the mechanisms considered, policy makers face a trade-off emissions certainty in particular periods and abatement cost reductions.

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Appendix

Table 2. Policy Comparison—Firm-Optimal Issuance Path

	Emissions (Gtons CO_2)			NPV costs ($ in billions)			
Policy	2.5%	Mean	97.5%	2.5%	Mean	97.5%	Details
Price							
Tax	166.7	187.4	209.2	464.5	464.5	464.5	
Hybrid							
Collar 1, *X* = $10							
Bank/Restr. Borr.	171.3	187.4	202.2	407.9	467.8	555.2	$a = 4.6$, $b = 5.4$
No Bank/Borr.	173.3	187.4	202.0	390.3	472.2	558.8	$a = 5$, $b = 5$
Collar 2, *X* = $20							
Bank/Restr. Borr.	175.5	187.4	196.7	362.3	474.2	631.2	$a = 9.1$, $b = 10.9$
No Bank/Borr.	178.5	187.4	196.4	343.7	487.3	644.3	$a = 10$, $b = 10$
Safety Valve 1							
Bank/Restr. Borr.	182.7	187.4	201.2	312.6	471.1	563.4	$a = 4.6$, $\varphi = 0.19$
No Bank/Borr.	179.1	187.4	201.5	366.0	486.3	571.9	$a = 5$, $\varphi = 0.12$
Safety Valve 2							
Bank/Restr. Borr.	185.4	187.4	195.7	292.3	477.0	644.1	$a = 9.1$, $\varphi = 0.40$
No Bank/Borr.	182.5	187.4	195.6	332.2	497.7	656.6	$a = 10$, $\varphi = 0.35$
Quantity							
Unlmtd. Bank/Borr.	187.4	187.4	187.4	270.9	473.5	745.3	
Bank/Restr. Borr.	186.8	187.3	187.4	273.7	488.7	786.0	
Bank Only	187.4	187.4	187.4	273.5	489.3	785.6	
No Bank/Borr.	187.4	187.4	187.4	318.2	522.5	790.5	

Notes: 2.5% and 97.5% refer to the lower bound and upper bound, respectively, of the 95% confidence interval based on the simulation procedure. Banking is unrestricted for all policies with banking allowed. Quantity policies are cap-and-trade only policies. Abbreviations: Borr., Borrow; Restr., Restricted; Unlmtd., Unlimited.

Table 3. Policy Comparison—Constant-Decline Issuance Path

Policy	Emissions (Gtons CO_2) 2.5%	Mean	97.5%	NPV Costs ($ in billions) 2.5%	Mean	97.5%	Details
Price							
Tax	166.3	187.4	209.7	510.3	510.3	510.3	
Hybrid							
Collar 1, *X* = $10							
No Bank/Borr.	173.3	187.4	202.0	423.0	518.2	615.1	$a = 5, b = 5$
Collar 2, *X* = $20							
Bank/Restr. Borr.	175.8	187.4	195.5	383.9	512.9	705.1	$a = 12, b = 8$
No Bank/Borr.	178.5	187.4	196.4	362.9	532.8	712.5	$a = 10, b = 10$
Safety Valve 1							
No Bank/Borr.	179.5	187.4	201.5	363.0	519.3	633.8	$a = 5, \varphi = 0.11$
Safety Valve 2							
Bank/Restr. Borr.	185.9	187.4	193.4	297.6	510.1	739.4	$a = 12, \varphi = 0.26$
No Bank/Borr.	183.7	187.4	195.5	327.8	532.8	723.2	$a = 10, \varphi = 0.31$
Quantity							
Unlmtd.Bank/Borr.	187.4	187.4	187.4	270.3	473.5	745.5	
Bank/Restr. Borr.	186.8	187.3	187.4	291.5	537.5	882.4	
Bank Only	187.4	187.4	187.4	291.8	537.9	882.4	
No Bank/Borr.	187.4	187.4	187.4	319.2	571.9	896.6	

Notes: 2.5% and 97.5% refer to the lower bound and upper bound, respectively, of the 95% confidence interval based on the simulation procedure. Banking is unrestricted for all policies with banking allowed. Quantity policies are cap-and-trade only policies. Abbreviations: Borr., Borrow; Restr., Restricted; Unlmtd., Unlimited.

Table 4. Constantly-Declining Issuance Path, Firm-Optimal Price Mechanisms

	Emissions (Gtons CO_2)			NPV Costs ($ in billions)			
Policy	2.5%	Mean	97.5%	2.5%	Mean	97.5%	Details
<u>Hybrid</u>							
Collar 1, *X* = $10							
Bank/Restr. Borr.	170.1	187.4	205.9	416.3	469.2	513.0	a = 3.8, b = 6.2
No Bank/Borr.	171.6	187.4	204.8	409.3	473.2	529.8	a = 4.9, b = 5.1
Collar 2, *X* = $20							
Bank/Restr. Borr.	173.8	187.4	202.5	377.3	480.8	569.9	a = 7.8, b = 12.2
No Bank/Borr.	176.0	187.4	200.8	374.5	492.3	597.9	a = 9.8, b = 10.2
Safety Valve 1							
Bank/Restr. Borr.	171.7	187.4	205.5	388.0	475.4	542.5	a = 3.8, φ = 0.04
No Bank/Borr.	174.0	187.4	204.2	381.3	482.0	559.3	a = 4.9, φ = 0.05
Safety Valve 2							
Bank/ Restr. Borr.	180.5	187.4	201.3	341.5	487.1	606.0	a = 7.8, φ = 0.13
No Bank/Borr.	180.3	187.4	199.9	349.5	500.5	635.9	a = 9.8, φ = 0.13

Notes: Results based on constant-decline permit issuance path and price mechanisms rising at the firm's rate of interest. 2.5% and 97.5% refer to the lower bound and upper bound, respectively, of the 95% confidence interval based on the simulation procedure. Banking is unrestricted for all policies with banking allowed. Quantity policies are cap-and-trade only policies. Abbreviations: Borr., Borrow; Restr., Restricted; Unlmtd., Unlimited.