Price-Responsive Allowance Supply in Emissions Markets

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Abstract: Environmental policy with uncertainty is often posed as a choice between price and quantity instruments. Adding flexibility to fixed policy instruments can improve outcomes. Roberts and Spence noted the efficiency advantages of matching emissions allowances supply to the marginal damage schedule. We propose an implementable approach to making that match, an approach we call "price-responsive supply," which treats prices and quantities as simultaneously determined in the allowance auction. For competitive environments, price-responsive supply outperforms fixed-price and fixed-quantity instruments. Price-responsive supply can enhance the performance of real-world regulatory environments through an automatic adjustment mechanism that responds instantaneously to new information about abatement costs. We demonstrate the improved performance of price-responsive supply in experiments and simulations. A price-responsive supply schedule, while offering efficiency advantages, also translates the cost-lowering effects of other, coincident policies into accelerated reductions under an emissions cap, thereby helping to resolve the waterbed effect.

JEL Codes: Q48, Q54, Q58

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THE QUESTION OF WHETHER TO USE PRICES (emissions charges) or quantities (tradable emissions allowances) to implement incentive-based regulation is one of the most persistent debates in the environmental economics literature (Montgomery 1972;

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Weitzman 1974). A related literature has discussed "hybrid" systems, where features of price and quantity instruments are combined using quantity triggers or price collars. The question is motivated by the search for an efficient instrument in the presence of quantifiable uncertainty about benefits and costs. We propose to replace the "prices *versus* quantities" perspective with one that unifies the two approaches into a price-responsive allowance supply—"prices *with* quantities"—a feasible instrument that simultaneously determines price and quantity in an auction, implementing an upward-sloping emissions allowance supply curve rather than a fixed price or fixed quantity.

Building on the Roberts and Spence (1976) description of a hybrid system, this approach starts with the recognition that prices and quantities are jointly determined outcomes of an economic process. They showed that, under uncertainty, making emissions allowances available along the current best estimate of the marginal damage schedule could achieve an efficient expected outcome. Implementing this approach has not been considered practical previously,[1] but the increasing use of auctions for allocating emissions allowances enables a dynamic adjustment of allowance quantity using reserve prices to match the expected marginal damage curve, as originally suggested by Roberts and Spence. Price floors and caps using reserve prices add guardrails that can be represented as horizontal segments of an otherwise vertical auction supply function. Price-responsive supply adds an arbitrary number of steps or even a positively sloped segment to the supply function that is used to settle allowance auctions.

Considering this new view of the emissions allowance supply as automatically adjusting to new information about abatement costs, we argue that emissions markets are inherently a more flexible instrument than a feasible emissions charge. We demonstrate experimentally how price-responsive supply can be implemented and that it can reduce price and revenue volatility. Using the examples of the Regional Greenhouse Gas Initiative (RGGI) and the Western Climate Initiative, we argue that initial steps toward implementing elements of price-responsive supply have been important contributors to the successful operation of these cap-and-trade regimes.

Along with the technical aspects of instrument choice, policy makers face several obstacles to implementing an economic policy instrument to regulate greenhouse gas emissions that contribute to climate change. First among these obstacles is that calibrating carbon prices at levels high enough to approximate marginal climate damages has not been generally politically achievable. One among many persistent reasons is the challenge of

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1. Roberts and Spence noted the problem of increasingly thin markets in their proposed implementation. Baumol and Oates (1988) dismissed the idea of price floors because previous programs had used free allocations, which suggests a contingent property right that would have to be taken away or purchased by the government if prices fell and allowances were retired.

economic competition from firms in unregulated jurisdictions. Disparate emissions pricing policies across jurisdictions cause economic and emissions leakage, constraining politically sustainable price levels.

We start with the recognition that policy makers may be prevented from approaching the problem purely as a matter of choosing the technical economic optimum that balances marginal climate damages with marginal abatement costs. One can imagine an adjusted marginal cost function that includes political and economic costs, which bound the policy maker away from the usual representation of the economic optimum. In this more complete representation of the policy maker's problem, one might expect policy to be at least partially oriented toward influencing the factors that create a difference between technical marginal costs and adjusted marginal costs as they are perceived in the policy process.[2] In fact, the adjusted marginal cost function is responsive to investments in technological change and infrastructure to lower marginal costs and policy coordination among jurisdictions to reduce leakage.[3]

The pricing of greenhouse gas emissions, in particular, faces a special challenge due to the subsidiary structure of governance under which local governments and civic organizations often take measures to reduce emissions. Under a quantity-based emissions cap, these measures do not yield additional emissions reductions and instead reduce the market price of the quantity instrument (emissions allowance) which reduces the price-based incentive for regulated parties to achieve emissions reductions. This phenomenon, known as the waterbed effect, would not be observed under an emissions tax.[4] But, in the political realm, advocates of climate policy may not see tangible assurance of emissions reductions under a carbon tax, as one might under an emissions cap that is declining over time. For this and other reasons,[5] emissions markets are more widely employed than taxes in climate policy. Meanwhile subsidiary actions intended to achieve reductions that are additional to those achieved by the market are common: the *Long-Term Strategy of the United States* (2021) describes four strategic pillars to achieving US climate goals, three of which (innovation, nonfederal leadership, and all-of-society action) are additional to federal leadership.

2. "We should not shoehorn the (climate policy) problem into familiar (economic) structures just because they are familiar. That approach simply fails to capture the issues at stake" (Oswald and Stern 2019).

3. There may even be a general opposition to the very idea of having politicians or a government agency setting prices.

4. The waterbed effect refers to the rebound from efforts to reduce emissions at one location that results in an increase in emissions at another location when total emissions are capped (Perino 2018).

5. For example, in many jurisdictions, emissions trading can be implemented under existing regulatory authority, but carbon taxes require legislative approval. Emissions trading programs have introduced measures to limit leakage and address competitiveness that do not yet have practical analogues implemented under emissions taxes.

When, via the waterbed effect, the market design effectively preempts the influence of additional efforts by subsidiary actors, it undermines strategic planning and political support for carbon pricing (Fankhauser et al. 2010; Dolan 2021).

Furthermore, in most cases, and especially in the context of climate policy, the regulator's problem is not a one-time choice of instrument under uncertainty but instead a sequence of policy choices selecting from an evolving set of achievable policy options. In practice, policy makers seeking to capture the promise of cost-effectiveness from carbon pricing have pursued an incremental approach. In a dynamic policy context, the climate policies we observe tend to follow a pattern foreshadowed in Baumol and Oates (1971), where regulators set a science-based target and chart a contingent pathway to that target. Everywhere, we observe that policy makers invoke a variety of "companion" policies to promote new technology and cultivate political alliances, aiming indirectly at reducing greenhouse gas emissions. Frequently, these policies are supported by investments of auction proceeds from the trading program. Over time, these activities contribute to changes in economics, politics, and technology that collectively influence the set of feasible policy options.[6]

This paper offers a novel contribution by reframing the conventional instrument choice for achieving an economic optimum from one of price versus quantity to one of implementing a single instrument that reduces the costs of uncertainty by reducing the frictions inherent in incremental policy responses to new information. Price-responsive allowance supply (as opposed to emissions prices or quantities alone) can help resolve the waterbed dilemma and enable the dynamic incremental process described by Baumol and Oates that can move policy toward a long-term target cost-effectively. Unlike quantity adjustment mechanisms for emissions taxes that adjust ex post in response to observed emissions, and price collars in trading programs that offer only guardrails on prices, a price-responsive allowance supply provides immediate and continuously responsive feedback to decision makers.

We investigate the performance of price-responsive supply functions in an experimental setting and in simulation modeling. We focus on changes to the marginal cost schedule that may be revealed by the resolution of uncertainty and more generally by changes that may be precipitated by companion policies. Compared to existing adjustment mechanisms that take effect only for specific changes or are implemented with a lag, we find that price-responsive supply improves the effectiveness of trading programs by instantaneously adjusting the quantity of allowances supplied to the market based on directly observed market signals about compliance costs.

When companion policies reduce technology costs and thereby reduce the allowance market equilibrium price, a supply response in the allowance market channels the

6. Incremental actions involving a portfolio of policy approaches with the intent of affecting obstacles to carbon pricing have been described as policy sequencing (Meckling et al. 2015; Meckling et al. 2017; Pahle et al. 2018).

reduced costs to achieve further emissions reductions.[7] Such a decline in the quantity of allowances supplied supports the allowance market price. Alternatively, when allowance market prices rise to levels greater than what policy makers view as politically sustainable, a price-responsive supply schedule expands allowance supply to reduce the price, protecting the political stability of carbon pricing. All of this is accomplished according to fixed, pre-announced decision rules, reducing regulatory uncertainty, which strengthens investor confidence relative to delayed and unpredictable administrative adjustments. The rule-based adjustment allows market participants to evaluate likely future outcomes based on their private information about market circumstances.

The experiments show that price-responsive supply reduces price volatility in allowance market equilibria. In our experiments, we demonstrate an early and persistent effect on allowance price levels and variability. We also find evidence that reduced variability in prices will lead to reduced variability in auction revenues, at least with a linear price-responsive supply, which is important to the planning of investments to accelerate emissions reductions.

A price-responsive allowance supply introduces new policy parameters, including the number of price steps in the supply schedule, and their size, which together determine the average slope of the schedule. We use a realistic simulation model of CO_2 emission reductions in the US electricity sector to demonstrate that a greater number of price steps is expected to lead to less auction revenue variability, reinforcing the findings from the experimental setting. Further, we show in the simulation model that the price-responsive supply function leads to changes in investment and power generation that achieve additional emissions reductions compared to an inelastic allowance supply.

Price-responsive supply reduces the risks that firms and policy makers face due to the combined effects of price variability and regulatory uncertainty. In most situations price-responsive supply yields more stable carbon revenues, facilitating public sector investments that drive new technology, and attracting growing political support for carbon pricing through the development of coalitions that benefit from new economic opportunity. The automatic policy updating of price-responsive allowance supply can help policy makers achieve long-term emissions reduction goals with rules that have the attractive political properties of being both adaptable and durable.

In the next section, we review the development of the literature on prices versus quantities. In section 2, we discuss specifics about how price-responsive supply is implemented and provide theoretical support for its value in policy updating. Section 3 describes an experimental investigation of the performance of this new approach to allowance supply. Section 4 describes simulation modeling that is used to provide guidance in the design of

7. Indeed, it is virtually always the case that substantial revenues from allowance auctions are dedicated to functions, such as research and development and energy efficiency, that tend to lower the demand for allowances (Burtraw and Keyes 2018; Löfgren et al. 2018). These types of expenditures put an endogenous downward pressure on allowance prices.

price-responsive supply. Section 5 describes the policy experience with price-responsive supply. Section 6 provides a concluding argument that price-responsive supply should be a fundamental characteristic of allowance market design, and in environmental markets generally, and points toward a set of research questions that surface as a result.

1. LITERATURE AND HISTORY

The prices versus quantities debate stems from the 1950s literature on economic planning, which concerned whether an agency responsible for administering an economic plan within centrally planned economies or large firms should use quantity output controls or administered prices to implement the plan.[8] Weitzman's "Prices vs. Quantities" paper (1974) focused not on environmental policy but on the older debate over the central planner's task.[9] Weitzman asked whether, "for some isolated economic variable that needs to be regulated," is it better to administer the activity directly (set the quantity) or to fix transfer prices and allow profit-maximizing firms to decide what is produced. Weitzman showed that if the cost of production is uncertain, one needs information about the shapes of the cost and benefit schedules to minimize the deadweight loss arising from uncertainty over production costs. His main point was that neither prices nor quantities would be preferred for all situations. Adar and Griffin (1976) and Fishelson (1976) independently of each other and of Weitzman demonstrated the importance of the marginal cost and benefit functions in choosing between price and quantity instruments for emissions control.

At the same time, Roberts and Spence (1976) independently pointed out that, under uncertainty over abatement costs, the regulator generally can do better by mixing prices and quantities rather than depending on one or the other. They show that, if marginal pollution damages are constant, then there is no benefit to a mixed policy instrument. But, if marginal damages are rising, then a mixed system of "charges and licenses" that better approximates the social marginal damage schedule can outperform either instrument alone. The policy maker chooses the number of licenses to sell (the cap) and two "escape valve" prices—a price, p, at which more licenses will be made available if the emitter wishes to buy them and a subsidy value, s, granted to the firm for the extent to which its emissions fall below the number of licenses it owns. The policy maker sets the number of licenses so that, with expected abatement costs, the value of licenses will equal marginal abatement costs and will fall between p and s. If costs are unexpectedly high or low, then the price mechanism will be binding. With many firms, the license price can be established in a competitive market for the licenses.

8. Our focus here is only on the prices vs. quantities debate. For a detailed discussion of the history of the idea of pricing pollution, see Banzhaf (2020).

9. In the same year, Weitzman began a series of papers on common pool resources. This was the start of his long career of notable contributions to the environmental economics literature.

Various options for relaxing the fixed nature of the allowance supply have been included in climate policy proposals, including (1) a circuit breaker that would stall the rate of decline of an emissions cap at a specified price trigger, (2) an independent board established to manage the supply of allowances to keep prices within an acceptable range, and (3) a price collar setting a ceiling and floor on the price of emissions allowances (Pizer 2002; Aldy and Pizer 2009; Murray et al. 2009; Burtraw et al. 2010). In a variation on the last design, Karp and Traeger (2018) propose a redemption-value function that uses the market clearing allowance price to adjust the emissions value of each allowance certificate.[10] Existing programs do not have circuit breakers or independent boards, but they do have a regularly scheduled review that often leads to administrative adjustments to supply. A price collar of some form is also used in many existing cap-and-trade programs. At the price ceiling, additional allowances are made available, and at the price floor allowances are withheld from the market. In this framework, traders face a stepped supply curve for emissions allowances, which generally is a better approximation of the marginal damage function than either a fixed fee or a fixed cap.

Similar mechanisms are envisioned with respect to how an emissions fee could be adjusted to achieve a specific emissions goal, sometimes called an emissions assurance mechanism (Newell et al. 2005; Metcalf 2009; Aldy et al. 2017; Hafstead and Williams 2017).[11] Virtually all discussions start from one of the two conceptual approaches, quotas or fees, and explore modifications that make one look like the other or, potentially, offer a hybrid of the two approaches. The ability of the policy to respond to new information is key to performance in all these models. All these approaches differ in one important respect from virtually every commodity market—changes in allowance supply are implemented with a lag and some degree of discretion, while the supply of a commodity responds automatically and systematically with the equilibrium price obtained in the market.

Our approach is closest to Roberts and Spence (1976), who in an appendix generalized their hybrid mechanism by offering distinct assets at arbitrarily many steps (cap levels), each with its own price collar. Such a schedule can closely approximate any convex damage function, lowering the expected welfare cost of uncertainty over abatement costs. A challenge of implementing this multistep mechanism is that the markets for the increasing number of distinct assets, one for each step in the supply, become thin and will not be

10. The EU Emissions Trading System recently enacted a market stability reserve (MSR) to adjust the supply of allowances based on the number of allowances in circulation (the bank). The program removes allowances from auction and places them in the reserve when the privately held bank is larger than a specific size. Beginning in 2023, a portion of allowances held in the MSR is canceled when the reserve grows to a specific size. For analysis of some of the difficulties with this approach, see Holt and Shobe (2016a), Perino and Willner (2019), Rosendahl (2019), and Osorio et al. (2021).

11. See also the recent forum in a 2020 issue of the *Review of Environmental Economics and Policy*, https://academic.oup.com/reep/issue/14/1.

competitive.[12] To solve this dilemma, we propose a feasible implementation of the multistep market that does not divide up the allowance supply in a way that reduces competitiveness.

We also compare our approach to Pizer and Prest (2020), who provide analysis of the relative performance of emissions charges and emissions markets in a dynamic context where new information about emissions damages and abatement costs emerges over time and where policy can be updated in response. They describe a case where policy updating with error favors the use of emissions charges over emissions markets. In the next section, we will argue that price-responsive supply will be preferred to emissions charges, even in the case of erroneous policy updating. We also argue that policy makers may in fact make decisions intended to affect the costs and benefits of other policy choices.

2. THEORY AND APPLICATION

In this section, we describe price-responsive supply in more detail and present some theoretical results demonstrating its likely advantages over the traditional approach of emissions charges or fixed-quantity emissions markets. We will first show that, in the static policy context, where there is uncertainty over both marginal abatement costs and marginal damages, our approach will, under reasonable conditions, accomplish the improved outcome first suggested by Roberts and Spence (1976). We will then extend these results to the case of policy updating recently explored by Pizer and Prest (2020). Because price-responsive supply updates the cap level as new information about costs is revealed, it eliminates the advantage of emissions charges even in the case where the policy maker is subject to a randomly determined policy bias in later periods. Drawing on observed experience in existing emissions markets, we will also argue that responsive supply has a practical information advantage for policy makers who face the task of updating policy in light of new information about marginal abatement costs; that is, it is easier for policy makers to discover new information about marginal cost using responsive supply than using updated emissions charges.

2.1. The Static Case

Roberts and Spence prove that, for a given expected marginal damage schedule, a combined quantity and price regime reduces expected efficiency loss from mistakes in estimating the marginal abatement cost schedule. They demonstrate that dividing the cap into a sequence of assets each with its associated price-quantity step can approximate the

12. Roberts and Spence (1976, 204) show that "if one is prepared to introduce more than one kind of license, the penalty function can be made to approximate any convex damage function arbitrarily closely." But they also note that each of the asset markets must have enough participants "to ensure relatively competitive functioning."

marginal benefit schedule arbitrarily closely, eliminating the expected deadweight loss in the limit.

The proof posits a sequence of increasingly smaller markets for each set of licenses as the marginal damage schedule is divided into smaller segments. In principle, the resulting difficulty of market thinness can be overcome by recombining the separate assets into a common cap and selling the emissions allowances in an auction that determines both the quantity sold and the closing price based on the bids in the auction. In the appendix (available online), we provide a simple proof that selling a supply of allowances at auction along the expected marginal benefit schedule, implemented in an auction where bidders in the auction bid truthfully, eliminates the expected loss from mistakes in estimating marginal abatement costs, as is the case with the Roberts and Spence sequence of license markets.

Although truthful bidding is not generally guaranteed, there is reason to believe that feasible auction mechanisms may produce outcomes close to those designed for inducing truthful bidding. Montero (2008) proposed an auction mechanism that can induce truthful bidding when auctioning along a supply schedule. While Montero's suggested design would be difficult to implement in practice, Requate et al. (2019) show that for reasonably competitive auctions, little efficiency is lost by using a simple uniform price auction of the sort now used in many emissions trading programs across the globe.[13]

With the near-truthful bidding that can be expected in competitive uniform-price auctions, the deviation of the auction closing price from the marginal abatement cost can be expected to be small. If the allowance auctions can be made competitive, then the policy maker's actual policy choice is between the likely loss of efficiency in using a standard, uniform price auction to implement a price-responsive supply of emissions allowances and the likely efficiency loss from selecting the wrong emissions charge.

2.2. Policy Updating over Time

In a dynamic setting with policy updating in response to new information, we use the Pizer and Prest (2020) multiperiod model to show that, even with nonoptimal second-period policy making, price-responsive supply is superior to emissions charges under the assumption that the emissions allowances can be auctioned under conditions where the closing price at auction is equal to the marginal abatement cost. In Pizer and Prest, the information aggregation function of markets can go astray due to perverse policy outcomes in the second period. In effect, we do not want the market to anticipate bad future policies; the inability of market participants to act now on the perverse things the policy maker will do in the future is an advantage.[14] This result depends on the assumption that

13. Khezr and Mackenzie (2018a) discuss administratively manageable ways of implementing the Montero auction design.

14. We note that there are many variations on this theme, and one should be cautious about attaching too much generality to one of the infinite ways that policy making may diverge from

policy adjusts slowly compared to firm expectations. Firms observe new information about costs and benefits and act on this before observing the inefficient policy response. The price-responsive supply approach adjusts policy contemporaneously with the revelation of new information and, in doing so, eliminates the second-period cost that arises from firms acting before bad policies are revealed. So, even with the bad second-period policy, emissions charges no longer have the advantage.

Theorem: In the Pizer and Prest two-period case, where the policy maker uses a biased (shifted) estimate of the marginal damage function for policy updating in the second period, price-responsive supply is always better than an emissions charge.

Proof: Using the familiar setup from Weitzman (1974) where costs and benefits (in terms of emissions abatement rather than emissions) take the following forms:

$$C(q,\theta) = c_0 + (c_1 + \theta)(q - \hat{q}) + \frac{c_2}{2}(q - \hat{q})^2, \tag{1}$$

$$B(q,\eta) = b_0 + (b_1 + \eta)(q - \hat{q}) - \frac{b_2}{2}(q - \hat{q})^2, \tag{2}$$

where q is emissions abatement, $\hat{q}$ is the abatement target, η is uncertainty over damages, and θ represents uncertainty over costs, we know that it is optimal to set expected marginal benefits equal to expected marginal costs, $E[\mathrm{MB}(q,\eta)] = E[\mathrm{MC}(q,\theta)]$. But in the Pizer and Prest case, the policy maker is constrained to using a biased marginal benefit measure in the second period:

$$\mathrm{MB}(q,\eta) + \epsilon,$$

where ϵ is a measure of policy bias in period 2. Pizer and Prest compare an emissions charge to a cap. We replace their traditional quantity cap by a price-responsive auction in both periods. For each period, the emission cap (auctioned amount), which is the policy variable $\hat{q}$ in equations (1) and (2), is set so that price is equal to the marginal benefit of reducing emissions. In the first period, the auction is settled according to the expected marginal benefit curve:

$$p_1^{\text{auction}} = b_1 + b_2 \cdot q_1^{\text{auction}}.$$

In the second period, having observed η, we auction along the biased marginal benefit function used by the policy maker:

the economist's ideal. Presumably, if the bad policy came first, to be followed by good policy, then the calculus would tip in favor of emissions markets.

$$p_2^{\text{auction}} = b_1 + b_2 \cdot q_2^{\text{auction}} + \eta + \epsilon.$$

The price-responsive supply auction will be preferred whenever[15]

$$\frac{-b_2^2 \sigma_\theta^2}{2c_2^2(b_2 + c_2)} < 0.$$

Since this is always true, then the price-responsive supply auction, even along the biased marginal damage function, is always preferred to updating a Pigouvian tax using the same biased marginal damage function.[16] So, a price-responsive auction outperforms a Pigouvian tax in all cases of policy updating studied by Pizer and Prest. QED

Once again, the comparison of the next best policy to price-responsive supply boils down to comparing any inefficiencies due to deviations in the auction price from the efficient price to any inefficiencies due to the setting of the incorrect sequence of emissions charges.

2.3. Applying Price-Responsive Supply to Policy Adjustment in Emissions Regulation

Modeling current carbon policies as dynamically equating marginal costs and benefits over a 200-year horizon is an important and useful academic exercise to guide research and development, investment, and policy design, but it is decidedly not how global warming policy is actually made in practice. As laid out by Baumol and Oates (1971), the practice of environmental policy making seems generally to start with a scientific result about damages due to the overuse of some resource or environmental service. The policy conversation often revolves around the question of how much of our limited regulatory budget should we be willing to spend to get the level of damages down to some acceptable level. The perceived cost of achieving given levels of reduction determines both the goal itself and the rate of approaching it. Policy makers establish a "budget" for spending resources on this good that we wish to "purchase" via our regulations designed to achieve the desired goal. For greenhouse gas emissions, this may amount to recursive rebalancing of emissions targets to equate marginal benefits and marginal costs in light of new information (Aldy et al. 2021) or to determining how quickly we can get to net zero (Stern and Stiglitz 2021) without busting the politically established social budget for doing so. This is not a one-shot decision. Everyone involved knows that new science will develop over time, production technologies will change, and new information about costs of achieving the goal will become available. The estimates of the marginal cost and marginal damage

15. Demonstration of this result is provided in the appendix.

16. The second-period result is the same for both policies. The superiority of the auction comes exclusively from the improvement in the first-period outcome.

schedules will be updated. That policies change with new evidence should not surprise anyone involved, but how they change can have a significant effect on outcomes.[17]

Existing emissions markets set emissions caps that fall gradually over time in order to help stay within the social budget by preventing the stranding of large amounts of existing capital assets and by allowing the development of new technologies that may lower the total costs of eliminating emissions. Initial prices in emissions markets, and carbon markets in particular, have often been lower than anticipated by policy makers and economists, and this has been accompanied by extensive banking of future allowances. The magnitude of the mistake in setting the cap level can be very large, as was the case, for example, for the European Union Emission Trading System (EU-ETS), the US Acid Rain Program, and the US Regional Greenhouse Gas Initiative (RGGI) cap.

In the case of the RGGI cap, between the time that the initial cap was set and the opening of the market, dramatic changes had taken place in related markets. In particular, the price of natural gas had fallen from nearly \$14/million Btu (mmBtu) in 2005 when the initial memorandum of understanding launched the multistate initiative to \$3 in 2009, the first year of the trading program. The RGGI allowance auction closed at the price floor for 11 consecutive auctions from the middle of 2010 until early 2013, when the RGGI states agreed to cancel allowances that had not been sold at the price floor and to halve the annual allowance allocation to accommodate a large private bank that had accumulated. A second adjustment to lower the cap occurred in the 2017 program review. Policy makers confided that the regulatory negotiations involving multiple jurisdictions in these decisions were "painful."

It also is likely that carbon policies are constrained away from what we might consider an efficient pathway by a variety of political and economic factors. Recent experience suggests that carbon markets operate in an environment driven to a substantial degree by companion regulations at various levels of government that direct technological change or that address complementary environmental goals such as local air and water quality or economic inequality (Fischer et al. 2021; Perino et al. 2021). Many of these companion policies would tend to suppress allowance prices under an existing cap. Policy makers seeking to achieve emissions reduction goals use companion policies to put a finger on the scales in favor of lowering emissions. These other policies can erode the price signal from the carbon market unless there is an explicit adjustment in the market to accommodate exogenous factors.

To strengthen the influence of a price signal and adjust regulatory stringency, carbon markets often apply administrative (discretionary) adjustments to the cap during periodic program reviews. For example, the RGGI memorandum of understanding incorporates a triennial program review to assess how the program is performing relative to previous

17. It is possible that a regime hostile to good governance may come into power. In this case, rational social planner models are of little help except possibly to estimate the costs of suboptimal policies.

expectations. Between reviews, the lag in regulatory response to the occurrence of unexpected prices perpetuates the earlier policy mistake. A lag between the realization of cost information and the policy response to that new information amplifies uncertainty about the likely response, undermines confidence in the market, and may fuel advocacy for additional sector-specific policies, pushing allowance prices even further from cost-minimizing levels, and potentially aggravating a vicious cycle by reducing the influence of prices in achieving the environmental goal (Flachsland et al. 2019). Setting the supply schedule in advance and then auctioning along this supply schedule provides both advance notice about future potential policy adjustments and instant feedback through the auction closing price about market expectations of future abatement costs. In fact, spot prices in secondary markets would likely signal firm expectations even before the auction occurred.

Alternatively, if we set price expecting to adjust it in response to the abatement costs inferred from the quantity response, the policy maker cannot simply calculate marginal abatement cost from the observed quantity outcome, because the quantity observed is a function of the error in estimating marginal costs, which the policy maker does not observe. The policy maker will need multiple observations on quantity to estimate marginal abatement costs. This will require a wait, possibly for years, to see how the induced investment in new capital stock has changed emissions. And by the time measurement is feasible, circumstances may have changed enough so that the estimates are not a good guide of current abatement costs. As we have already shown, eliminating policy lag reestablishes the superiority of using forward-looking market exchange rather than emissions charges for regulating emissions.

A price-responsive allowance supply provides a rule-based approach to adjusting stringency in response to realized information about abatement costs, and it adjusts cumulative stringency over time to automatically keep costs within the range of the agreed-upon regulatory budget. Periodic reviews remain essential because the policy maker's assessment of marginal damages (i.e., the allowance supply schedule) underlying the price-responsive supply will likely change over time; nonetheless, a price-responsive supply reduces the magnitude of an administrative adjustment that may be required during periodic program reviews.[18] A rule-based approach continuously responds to new information about allowance demand and marginal costs that is revealed in the allowance price, eliminating regulatory lag within compliance periods, boosting confidence in the market. In contrast, observed quantities in response to an emissions tax do not serve the same information aggregation function. Dynamic tax adjustments must be retroactive, while markets provide price information immediately and are forward looking.

18. An additional argument in favor of quantity targets is the desire to avoid possible existence of tipping points in damages. Price-responsive supply that is aligned with marginal damages accommodates this desire as the marginal damage curve becomes increasingly steep in the neighborhood of potential tipping points.

Figure 1 illustrates variations of price-responsive supply. Panel *A* illustrates an emission cap with a price floor and price ceiling; between these two price points changes in allowance demand map into changes in allowance price with no change in emissions. Panel *B* illustrates an additional price step above the price floor implemented with a reserve price for a portion of allowances offered in an auction, a design implemented as an emissions containment reserve in RGGI. If demand falls in this market, prices are greater and emissions are less than in the market represented in panel *A*. Panel *C* represents a multistep emissions containment reserve, which would be more continuously responsive to changes in allowance demand. Panel *D* illustrates that the regulator

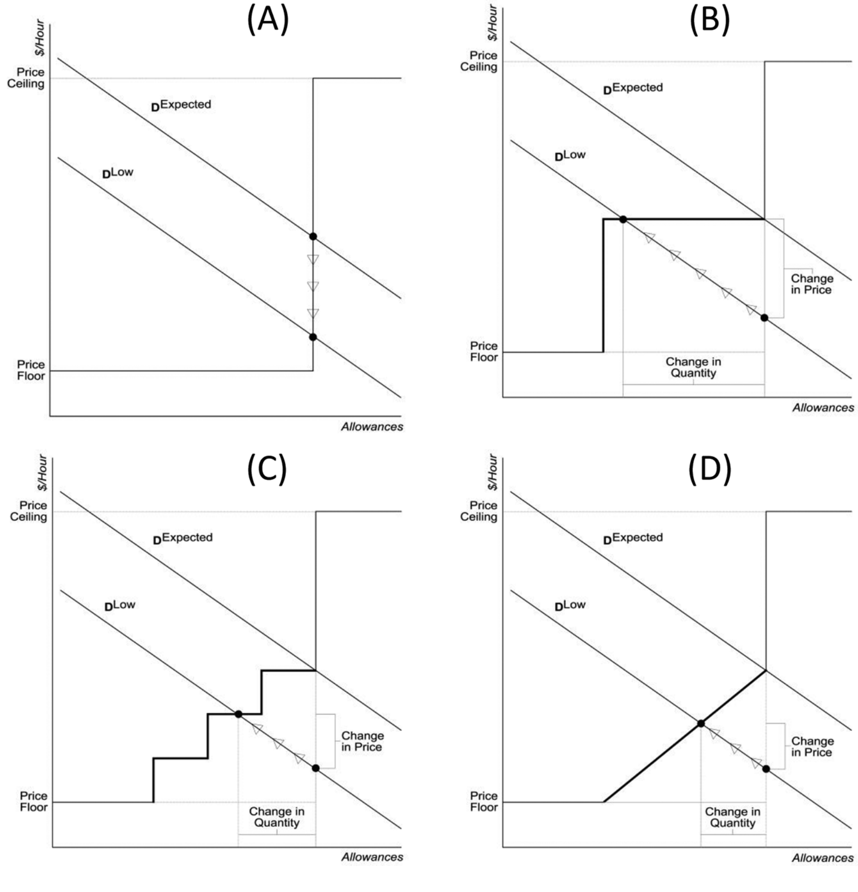

Figure 1. Variations of price-responsive supply in an emissions market. *A*, Emission cap with a hard price floor and soft price ceiling. *B*, Additional price step above the price floor implemented with a reserve price for a portion of allowances offered in an auction. *C*, A multi-step emissions containment reserve. *D*, Regulator specifies a smooth supply schedule and auction along this schedule.

could go so far as to specify a smooth supply schedule and auction along this schedule. In the next section, we will test the performance of the price-responsive supply mechanism in a set of experiments.

3. EVALUATING PRICE-RESPONSIVE ALLOWANCE SUPPLY IN A BEHAVIORAL CONTEXT

The implementation of a price-responsive supply uses bids in an auction to adjust the auction quantity. With added price steps, or with a smooth price-response function, the actual number of allowances sold will vary from the anticipated or nominal cap for that period. In our experiments, we test the performance of price-responsive supply that operates just below the expected, long-run equilibrium price given the nominal cap.[19] If the price-responsive supply mechanism in our setup is ever binding, then the allowance sales for that period will be below the nominal cap (vertical segment in the panels of fig. 1). This implies a tighter cap, compared to the same initial intended level without the price-responsive supply. As a result, forward-looking agents would anticipate the tighter cap and bid up allowance prices. This higher early price of allowances should persist over time, even in periods in which the price-responsive supply trigger point is not binding. Since a price-responsive supply mechanism dampens price reductions during slack demand periods, we expect price volatility to be reduced. Whether these expectations are realized depends on how well agents anticipate the effects of the mechanism and on the strategies they deploy when there is uncertainty about future payoffs from owning allowances. We test these implications using laboratory experiments with financially motivated human subjects.[20]

While there have been experiments testing the effects of reserve prices and price ceilings (Stranlund et al. 2014; Holt and Shobe 2016b), there have not been tests of how adding price-responsive supply affects market outcomes. In the case before us, we are interested in measuring the effect of adding price-responsiveness to supply in a simulated market designed to mimic some of the essential features of existing allowance markets.

Previous studies of the performance of price collar mechanisms, including its effect on banking, found that these mechanisms reduce the costs associated with uncertainty

19. The price-responsive supply mechanism can operate in either direction from the expected equilibrium price. We limit our focus to a mechanism operating just below the expected equilibrium price.

20. Experiments have been used previously to explore the effects of market designs in many of the key emissions markets implemented to date, including RGGI, the SO_2 allowance trading program, the eastern US NO_x market, the EU ETS, and the California CO_2 cap-and-trade program. In particular, laboratory experiments were a key component of the original consulting report proposing to set up the Regional Greenhouse Gas Initiative auction-based program (Holt et al. 2007).

over the future value of allowances (Cason et al. 2020).[21] Stranlund et al. (2014) used a multiperiod setting to show that, even in the presence of banking, price collars reduce price volatility, since market participants may not be able to smooth compliance costs sufficiently with banking alone. Cason et al. (2020) find that a hard price floor increases investment in lowering future abatement costs by increasing the expected return to that investment.

The results on the possible behavioral effects of price collars in static (single-period) settings is mixed. Perkis et al. (2016) found that soft collars were not as effective as hard collars in reducing price volatility. Friesen et al. (2019) examined different mechanisms for reducing high-price shocks. Their experiments suggest that supply reserves intended to dampen high-price shocks can under some circumstances lead to higher allowance prices.

Isaac and Plott (1981) reject the hypothesis that nonbinding price controls act as focal points for bidders in auctions for emissions allowances. More recently, Khezr and MacKenzie (2018b) identified conditions under which, in a static setting, an allowance reserve used to limit high allowance prices may alter auction clearing prices. In related experiments, Friesen et al. (2022) find that price collars may change bidding behavior in allowance auctions, pushing bids closer to price floors and ceilings.

In our experiments, we find, as expected, that price-responsive supply causes an early and persistent increase in allowance price and reduces price variability. We also find evidence that reduced variability in prices will lead to reduced variability in auction revenues, at least with a linear price-responsive supply function.

3.1. Experiment Setup

The experiments were implemented at the University of Virginia using the oTree experimental platform (Chen et al. 2016). Subjects were recruited in groups of 12 for sessions that lasted about 1.5 hours. Each session consisted of 30 periods or "rounds" that began with a 12-bidder auction and ended with the posting of earnings results based on the auction outcome and individual decisions on whether to use acquired allowances for current production or to bank them for future use. The auction mechanism used depended on the treatment; there were nine sessions in the no policy control treatment (as with fig. 1*A*). In addition, there were nine sessions with a single-step supply shift (fig. 1*B*) and nine sessions with a linear supply schedule (fig. 1*C*). In total, there were 27 sessions, each with a single fixed group of 12 bidders who competed in 30 consecutive auctions.

The laboratory setup presents subjects with a simplified version of a generic "permit" market, using neutral terminology that did not connect the permits needed for production to the notion of emissions allowances. Subjects can only acquire allowances in the auction; there is no spot market. The bidders interact through the determination

21. For a recent review of experiments on emissions allowance auctions generally, see MacKenzie (2022).

of the auction closing price based on all bids submitted, which in turn determines whether a supply adjustment is triggered.

Each of the 12 participants in a session controls four "capacity units" that produce one unit of output per period. Half of the participants were designated as "low users" (with low-emitting units), which require one permit per unit of output produced, while half were "high users" with units requiring two permits per unit of output. Output is sold at an exogenous price that was either $30 or $40 per unit, each with a probability of 50%. The shocks are uncorrelated. This output price variability induces periods with higher or lower current-use values for permits, which also depend on randomly determined costs that were independently generated for each bidder prior to the auction (details to follow). All sessions have the same random sequence of output prices and orthogonal cost realizations, so these factors are held constant across the three treatments.

Subjects are assigned a random cost of production for each of their capacity units in each round. Production costs vary uniformly on ($10, $28) per unit of output for low emitting units and on ($1, $28) for high emitters. The net value of a permit for current use is the difference between the current product price and the realized production cost for the unit, divided by the required number of permits needed to operate the capacity unit.[22]

Each of the 30 periods in a session begins with a uniform-price auction of the available allowances, sold at the highest rejected bid, and a production stage, in which subjects choose how many of their capacity units to run. The running of capacity units determines the number of permits that must be retired for compliance with the permit requirement. Running a unit without owning a permit to cover its operations incurs a substantial penalty ($35 per missing permit).

The number of allowances sold at auction starts at 66 in the first period of a session and declines by one allowance each period, going down to 37 permits auctioned in period 30. This pre-announced tightening of the cap provides an incentive to bank permits early on in anticipation of increased scarcity later. Previous experiments have shown participants to be adept at smoothing the supply of allowances over time, although they do so imperfectly (Shobe et al. 2014). This implies that the price in early sessions should provide a good signal about the long-range tightness of the cap. If there were no smoothing, we would expect to see the price rise as the cap falls, but with effective smoothing, the price in early periods will be very similar to the price in later periods.[23]

22. In low-price periods, this net value ranges from $1 to $15.50 for high emitters and from $2 to $20 for low emitters. In high-price periods, this net value ranges from $6 to $19.50 for high emitters and from $12 to $30 for low emitters.

23. For simplicity, the experiments are structured to have a zero discount rate, which yields a flat predicted allowance price trajectory in a model with perfect foresight. This simplification does not change the key results.

All auctions have a reserve price of $5, with no bids accepted below that price. The single-step supply includes 16 allowances at the $8 step. In contrast, the linear ramp supply declines smoothly from the trigger price of $8 down to the auction reserve price of $5. All sessions also include a "cost containment reserve" (soft price ceiling) of 10 allowances that will only be released into the auction if it would otherwise close at a price above $12. Therefore, all sessions have precisely the same structure except for the introduction of a price-responsive supply and the way it is implemented. The appendix contains instructions that participants received about changes in the supply of permits. The only difference in the instructions between the three treatments is description of the supply response on page 3 of the instructions.

Subjects were recruited from the University of Virginia student body. There were 324 participants in total, each of which received a $6 participation payment, plus a payment of 2.5% of experiment earnings that were added to an initial cash endowment of $150 lab dollars. Total cash earnings averaged about $30 per subject.

3.2. Experiment Results

Since there is no discounting in this setup, optimal permit management implies that permits will be used whenever their current use values are above a cutoff. To determine this cutoff, the total cap *S* (the sum of all auction quantities in all 30 periods without any supply withdrawals) is used to determine the *S* highest current use values (price minus cost divided by the required number of permits for that unit). The long-run supply (total cap) and demand (based on valuations in all periods) are equal at a price of $8. This would be the price if all allowances were used optimally, that is, if there were perfect smoothing of cost and price effects across periods, that is, banking of permits in early periods with current use values below this cutoff. If some allowances will be retired, then the increased scarcity of allowances would imply a higher long-run allowance price than the $8 level. Of course, subjects do not have the information about random demand realizations or the distributions of random production costs necessary to determine the optimal $8 current-use cutoff. If subjects anticipate a supply adjustment mechanism to be binding in some periods, then they might also expect that the aggregate supply of allowances will be reduced.[24] Given the ability of people to anticipate future scarcity, the likelihood that a supply reduction will be triggered will reduce the long-term supply of allowances, which should raise prices in initial periods relative to prices in the no supply adjustment control treatment.

Figure 2 clearly shows a pattern of higher average allowance prices for sessions with a responsive supply than for control treatment sessions. On average, prices for both types of responsive supply, step and linear, are higher than for the no-responsiveness

24. Salant et al. (2022) describe and test experimentally a storage model with a nonbinding price floor. They demonstrate the mechanism results in price floors pushing prices upward even when they are not binding.

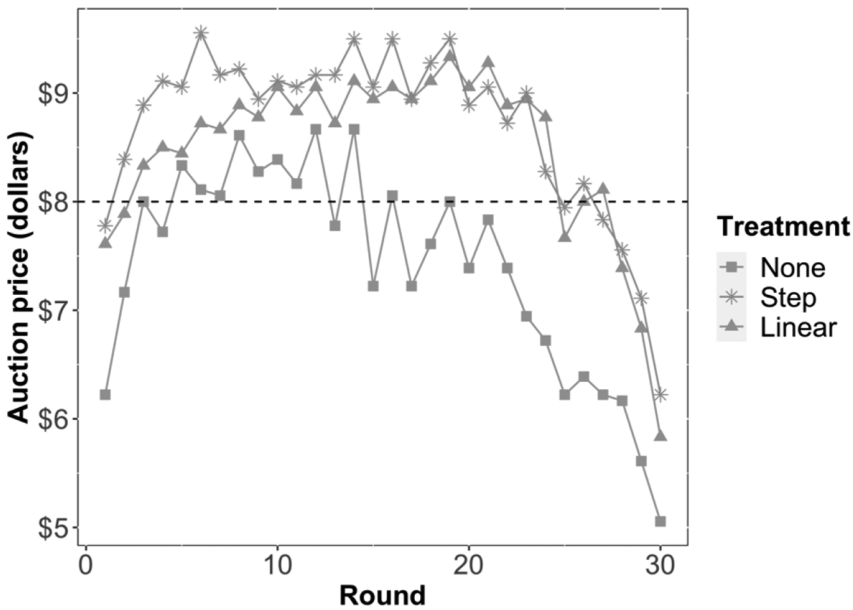

Figure 2. Average auction price by treatment by round

case in all periods. This difference is statistically significant, although the small difference between prices in the step and linear treatments is not.

Experimental result 1: Allowance prices are higher in price-responsive supply treatments.

Support: In order to avoid end effects, the average price for each session was calculated for the first 25 periods. With nine average price observations per treatment, the usual assumptions needed to justify a standard t-test are questionable. Therefore, we used a nonparametric permutation test that determines the proportion of the 48,620 permutations of treatment labels that produce a difference in treatment average prices that is as large as or larger than the observed difference in either direction (a two-tailed test). In this manner, the null hypothesis of no effect of the step supply relative to no supply response is rejected ($p = .0054$). Similarly, the null hypothesis for the linear supply relative to no supply adjustment is rejected ($p = .022$). These and all other permutation tests to be reported are two-tailed tests. These p-values for tests are almost identical to those obtained from a rank-based nonparametric test (Mann-Whitney). The numerical approach, using permutations of actual prices, can be justified when the underlying data are not ordinal.

Because the quantity of permits is not fixed, but rather is immediately responsive to demand during the auction, we expected to observe lower price volatility with a price-responsive supply. The lower price volatility of the responsive supply treatments relative to the no-responsiveness control is apparent from the sawtooth patterns in figure 2, which leads to our second result:

Experimental result 2: Allowance price volatility is lower in price-responsive supply treatments.

Support: Using the first 25 rounds of auction price data, the average of the absolute values of round-to-round auction price changes is calculated for each session, which provides nine independent variability measures per treatment. The average absolute value of the auction price change is 0.79 for the no-responsiveness sessions and 0.41 for the linear sessions. Only 1.4% of the permutations of the treatment labels yield a variability difference as large as this in either direction, so the result of a two-tailed permutation test of the null hypothesis of no difference can be rejected ($p = .014$). Similarly, for the step treatment, the average absolute price change is 0.44, which is also significantly different from the control treatment ($p = .038$). Finally, the null hypothesis that auction price variability is the same for the step and linear supply cannot be rejected ($p = .74$).

The use of a price-responsive supply could also change the incentive to bank allowances for the future. In theory, early banking could go either up or down in response to the presence of the supply adjustment mechanism. The lower observed price variability in the responsive supply treatments (result 2) suggests that there is less of an opportunity to accumulate permits at bargain prices in early low-demand periods, and as a result, banking could be reduced. Working against this possibility, some participants may wish to hold a higher bank in anticipation of fewer permits being available in the future. Our results are suggestive that the increased cost of accumulating a bank can be a powerful counterbalance to the desire to hold a larger bank in anticipation of future scarcity. As seen in figure 3, the average bank tended to be lower in the responsive supply treatments, especially in early periods.

Experimental result 3: The evidence that allowance banks are lower in price-responsive supply treatments is mixed but strongest in the early periods.

Support: The test uses the total bank for each session, averaged over the early periods (1–15). The null hypothesis of no difference is not rejected for step treatment ($p = .14$, two tails), but the analogous null hypothesis of no effect is rejected and for the linear treatment ($p = .098$, two tails). Using periods 1–25, the bank for the step treatment is not significantly lower than the no-response treatment ($p = .248$), but it is significantly lower for the linear treatment ($p = .094$).

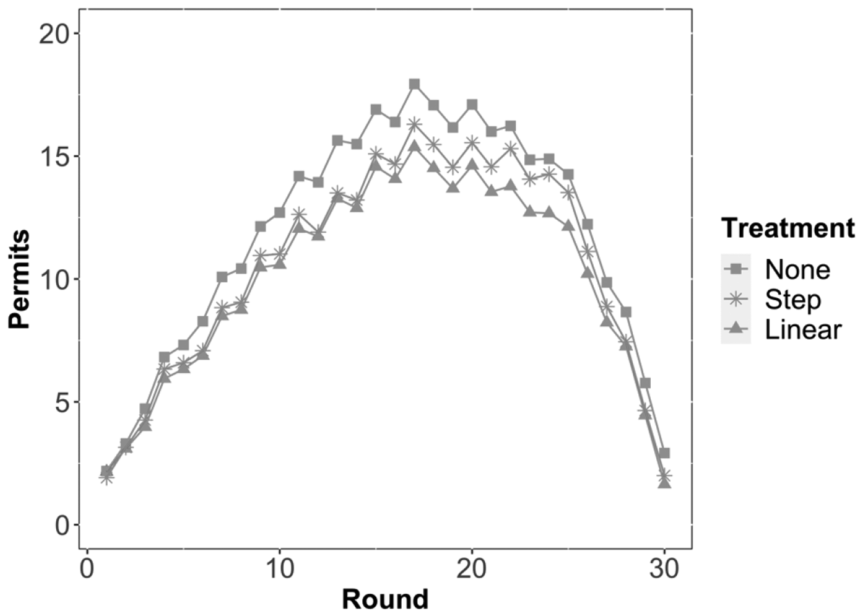

Figure 3. Total banked allowances by treatment by round

There is good reason to believe that lower price variability is generally beneficial. Policy makers also care about the revenue stability because revenue variability complicates budget planning. A price-responsive supply of allowances should tend to dampen price variability compared to a fixed cap. Some of the variation that would be loaded on price is now shared with variation in quantity, so the net effect on auction revenue is unclear. Figure 4 shows average auction revenues in each round by treatment. The largest revenue changes are for the middle periods of the no-response control treatment, as indicated by the sawtooth pattern of the lower line for that treatment. Of course, the significance of the result depends on the pattern of variability measures across independent sessions of each treatment, not just on overall averages. It turns out that auction revenue variability is significantly lower for the case of a linear supply, but not for a stepped supply, which leads to our fourth result:

Experimental result 4: Revenue volatility is lower with the linear supply but not with a step.

Support: Using the first 25 rounds of auction revenue data, the average of the absolute values of round-to-round revenue changes is calculated for each session. The treatment average auction revenue change is 46.37 for the no-response sessions and 28.37 for the linear treatment. Only 2.1% of the permutations of the treatment labels

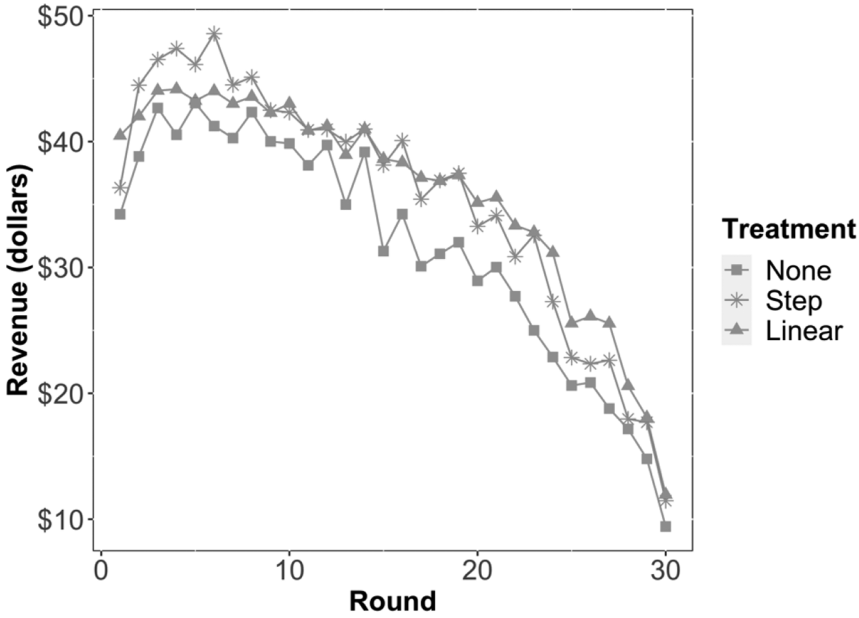

Figure 4. Total revenue per subject by treatment by round

yield a difference as large as this in either direction, so the result of a two-tailed permutation test is $p = .021$. In contrast, for the step treatment, the average absolute revenue change is 40.33, which is close to the observed 46.37 average for the control sessions, and the difference is not significant ($p = .48$, two-tailed). Finally, the null hypothesis that auction revenue variability is the same for the step and the linear responses can be rejected ($p = .056$).

Table 1 provides a summary of the treatment averages. As expected, we find that the price-responsive supply, step or linear supply, causes an early and persistent increase in auction prices above the $8 level (second column) and that price variability is reduced (third column). The price-responsive supply of allowances also results in a reduction in the size of the bank held during the early periods, although the difference is not uniformly significant. The reduced bank may be, in part, the result of reduced price variability due to the dampening effect of the price responsive supply. Finally, as shown in the right-hand column of table 1, the price responsive supply (step and linear) resulted in reduced revenue variability for the linear supply.

The final issue is how the different treatments affected the total production of both low and high users combined. The expected effects of the policy regimes on output in the product market are ambiguous, with two channels of influence, which operate in opposite directions. By canceling some allowances, and hence reducing aggregate

Table 1. Experiment Treatment Averages

Treatment	Average Price[a]	Price Variability[a]	Average Bank[b]	Revenue Variability[a]
No response	7.71	.79	10.27	46.37
Stepped supply	8.97***	.44**	9.04	40.33
Linear supply	8.74**	.41**	8.75*	28.37**

Note. The average price for each session is the average over the first 25 auction prices. Price variability is the average of the absolute values of period-to-period auction price changes in rounds 1–25. Revenue variability is calculated similarly using averages of absolute values of auction revenue changes in rounds 1–25. Average bank for a session is the average of the total bank held by all subjects in a session over the first half, rounds 1–15.

[a] Indicates an average for the first 25 periods.

[b] Indicates an average for the first 15 periods.

* $p < .10$ (for two-tailed permutation tests vs. no PRS).

** $p < .05$ (for two-tailed permutation tests vs. no PRS).

*** $p < .01$ (for two-tailed permutation tests vs. no PRS).

supply, the step and linear treatments would tend to raise the cost of production and reduce output. But the increased price due to the lower long-run supply would also cause a shift of production from high emitters to low emitters, a shift that would increase production for a given level of emissions. Our theory does not predict which of these effects is likely to be larger, so we are not able to say whether the amount of final output should rise or fall in our setup. In our experimental sessions, production of the final output is not statistically different among the treatments.

4. SIMULATIONS

The conceptual discussion in section 2 demonstrated the efficiency advantage of aligning the price-responsive supply of allowances with marginal damages. We use climate policy as a specific case for simulating price-responsive allowance supply, although the concept has general applicability in emissions markets. Some authors have suggested that the marginal damages of greenhouse gases are constant, implying that a tax would be preferred on efficiency grounds. But policy makers are likely to recognize air quality cobenefits that confer slope to the marginal benefits of carbon emissions reductions. And in the long run, the marginal benefit of greenhouse gas emission reductions is not constant, while indeed marginal abatement cost may become constant due to emergence of backstop technologies, suggesting a possible preference for quantity instruments in the Weitzman context. Practically speaking, having established that there are efficiency advantages in moving away from inelastic allowance supply in emissions markets (a strict cap), policy makers are left with the challenges of knowing the proper value of marginal damages for setting policy and implementing prices that approach this value. As policy makers incrementally expand carbon policies, one general concern is the volatility of

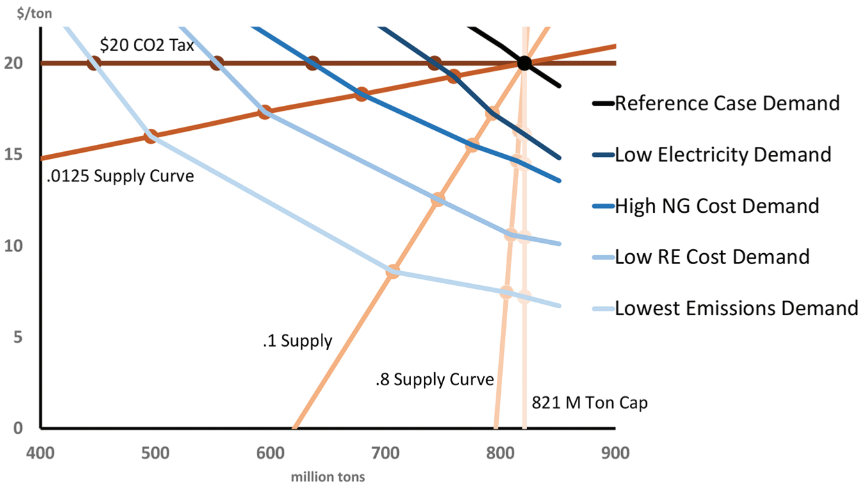

Figure 5. Electricity market equilibria with different supply and demand schedules

revenue in allowance auctions because revenue is tied closely to investments that are intrinsic to the design of climate policies.

To examine approaches to militate against revenue volatility and provide practical advice for policy makers we use a dynamic linear programming simulation model of the US electricity sector. The model solves for investment in and retirement of generation capacity over a 23-year horizon, with annual operation of the electricity system represented in four time blocks in each of three seasons. Electricity market equilibria are solved at the state level, allowing state-level representations of environmental policies and regulatory practice, with interstate transmission capability calibrated to observed transactions. We focus on 2026, a year sufficiently in the future to accommodate comprehensive carbon pricing in the electricity sector.[25]

We calibrate the CO_2 emissions market outcomes with an inelastic national electricity sector emissions cap of 821 million short tons, which is achieved at a price of $20/ton under reference case assumptions (fig. 5). We then explore alternative scenarios in the electricity market that reduce emissions allowance demand in the carbon market. These alternative scenarios include a 4% annual decrease in renewable cost, a 1% annual decrease in electricity demand, and a 20% increase in natural gas fuel cost in 2026. With inelastic emissions allowance supply, changes in the derived demand for allowances map entirely into changes in the price of allowances. Low renewable costs yield an allowance price of $10.47, low electricity demand yields an allowance price of $16.10, and the

25. The model does not allow intertemporal banking of emissions allowances to facilitate comparison with an emissions tax.

high natural gas price yields an allowance price of $14.46.[26] If all three of these outcomes occur simultaneously, we observe the lowest emissions demand and a price of $7.20. Conversely, allowance prices would increase if scenarios caused allowance demand to increase above reference case levels. Here we focus exclusively on outcomes that lower allowance demand, with a special interest in outcomes regarding renewable prices and energy demand that are likely to be affected by coincident policies. Cases when allowance demand falls in relation to reference case projections align with the dominant observed phenomena in environmental markets as discussed in section 2. An inelastic supply of emissions allowances translates all changes in market fundamentals into price movements, yielding high price and revenue variability. Total allowance revenues fall from $16.41 billion in the reference case to $5.91 billion when all three outcomes occur simultaneously in the lowest demand scenario. Other things being equal, policy makers would prefer a design that lessens revenue variability,[27] an important concern for emissions trading programs that increasingly are described as "cap and invest" meaning that emissions reductions are explicitly intended to result from the investment of auction revenue.

We explore the effect of price-responsive supply on revenue volatility. Two main new features characterize the design of a price-responsive allowance supply schedule: the (average) slope of the schedule and, if it has discrete steps, the number of steps. In the simulations displayed in figure 5, we consider three continuously differentiable linear allowance supply schedules (ramps with no discrete steps) with slopes of 0.8, 0.1, and 0.0125, in the southeast quadrant illustrating the region where demand for allowances falls relative to the reference case. Across potential equilibria identified by intersections of allowance supply and demand, less slope in allowance supply (more elastic supply) results in greater responsiveness in the emissions outcome when the demand for allowances falls compared to the reference case. Concurrently, the less slope in allowance supply, the less responsive is the allowance price.

Among the equilibria illustrated along each demand curve, we calculate revenue to be greater on the flatter allowance supply curves than on the steeper ones, although not as great as under the carbon tax which is perfectly elastic.[28] In general, whether revenues are best preserved under a quantity or price constraint depends entirely on the price elasticity of demand in the allowance market.[29] At the reference case equilibrium, we calculate an

26. Allowance prices fall with higher natural gas prices because in this neighborhood of carbon prices the main margin for achieving incremental emissions reductions is substitution between gas and renewables. Little coal generation remains in the system.

27. For example, in May 2021 Washington enacted its Climate Commitment Act to create an economy-wide cap on greenhouse gas emissions, with a central feature of an allowance auction that would yield revenue for investments.

28. We assume under every scenario that unsold allowances are permanently canceled and do not enter the market at a later date.

29. If demand falls, the change in revenue would be minimized if the slope of the supply schedule were the negative inverse of the slope of the demand curve.

allowance demand elasticity of –0.6, and at every allowance market equilibrium over the range of carbon market outcomes we examine we find allowance demand to be inelastic. With such a low elasticity of demand, revenues are best preserved under a CO_2 tax equal to $20, the reference case price observed in the carbon market. Under a tax, low electricity demand results in a reduction in emissions from 821 million tons to 743. Low renewable costs result in emissions of 554 million tons, and high natural gas costs result in 637 million tons. All three changes together in the lowest demand scenario result in emissions of 447 million tons. In this case, revenues from the carbon price fall in proportion to the change in emissions, from $16.41 billion in the reference case to $8.93 billion.

Revenue stability is one of many criteria shaping program design and other criteria including aversion to potential emissions increases often tip toward an allowance trading approach. The general guidance in an allowance-based system in the US electricity sector is that if demand for allowances falls, revenue will be more stable the flatter is the supply schedule.

The second new design feature relevant to the implementation of price-responsive allowance supply is the number of discrete price steps.[30] To enable comparability of price steps with the price ramps, we construct step function supply curves with an average slope of 0.1, the middle case illustrated in figure 5, for prices above the price floor of $9.50. We assume that steps along the supply schedule are of even height and evenly spaced.

Taking the reference case demand for emissions allowances from the simulations as a point of departure, we build a discrete distribution of 14 parallel and evenly spaced derived demand curves for emissions allowances ranging from the expected value in the reference case (with an equilibrium price of $20/ton and emissions of 821 million tons identified previously) to the lowest derived demand that intersects the supply curve where it hits the price floor.[31] With this distribution of potential realizations of allowance demand, we compare a linear supply curve (ramp) and a step function with the same average slope and up to nine price steps. The demand curves and three supply schedules including one step, three steps, and a ramp are illustrated in figure 6*A*.[32]

In the figure, one can observe that for any specific realization of demand, auction proceeds might be greater under the one step, three step, or ramp supply schedule. However, under restrictive but intuitive conditions about the distribution of expected changes in allowance demand, we find that a greater number of price steps maps into greater expected revenue on average over the indicated range of possible realizations with the

30. An additional feature is how the steps adjust over years, which influences investment. The price floor in the Western Climate Initiative and the emissions containment reserve in RGGI increase at 5% per year (real dollars).

31. The reference demand curve has an elasticity of –0.1 at the $20 allowance price, which establishes the slope of all the demand curves.

32. If the allowance supply schedules were illustrated in fig. 6 as continuing above the reference point, the reference point would bisect a vertical portion of the steps.

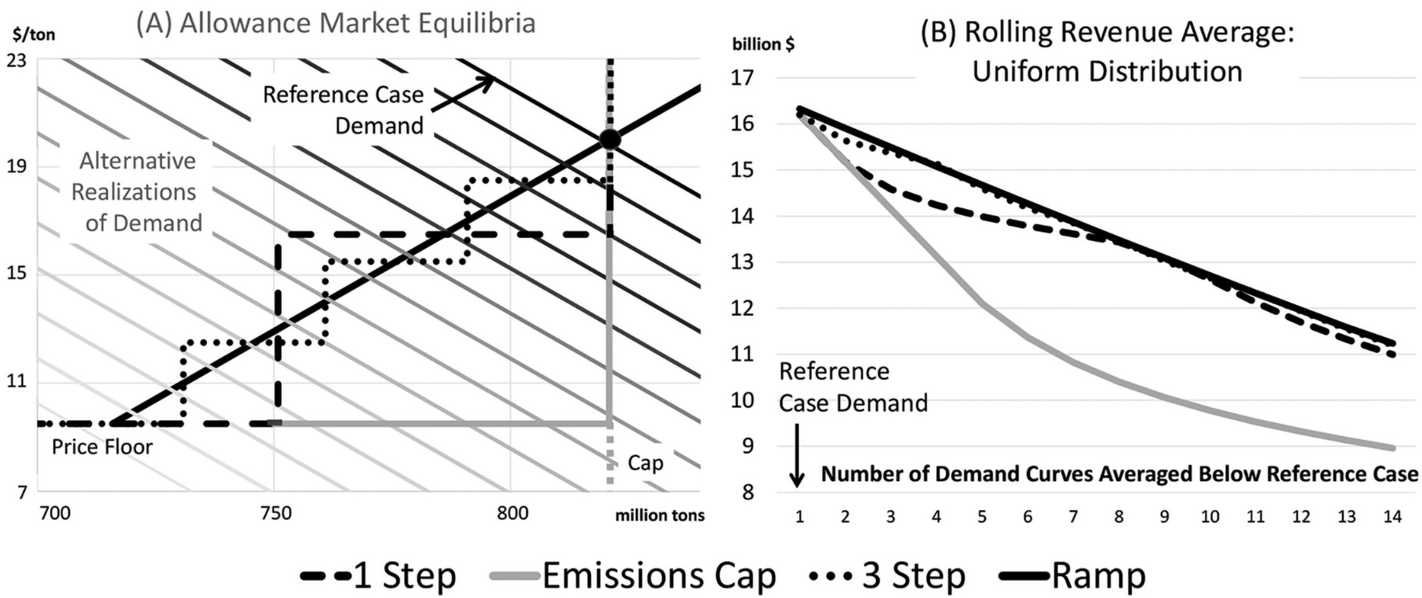

Figure 6. Realizations of allowance demand and alternative supply schedules

linear schedule implicitly having the most steps. We calculate expected revenue initially assuming a uniform probability distribution of potential demand outcomes anchored at the reference case demand with a support spanning to include from 1 to 14 of the demand curves illustrated in figure 6*A*. Variation in demand for allowances stems from the policy and secular shocks to costs like those modeled above. Figure 6*B* shows a rolling average of revenue as the support for possible demand realizations is expanded, beginning with the reference case demand curve, and broadening to include additional lower demand curves in sequence all the way down to where demand intercepts the price floor. For up to nine price steps and a continuous ramp, revenue is always greater at each potential equilibrium than under an inelastic allowance supply (a cap), and multiple price steps always outperform a single price step.[33] We also examine a one-sided triangular distribution of demand curves with the mode at the reference case and varying support ranging from one to all 14 demand curves, we examine supply curves with steeper (0.8) and flatter (0.0125) slopes illustrated in figure 5, and we vary the slopes of the parallel demand curves including steeper (−0.2) flatter (−0.05) demand, and find the same result.

In summary, in the electricity sector, which has been most often included in emissions markets, and where the demand for emissions allowances is generally inelastic, we conclude that revenue will be closer to expected revenue if alternative realizations of uncertain allowance demand results in relatively greater changes in the quantity of emissions and smaller changes in the price. This argues for a supply schedule that has a relatively flat slope. For a supply schedule with a given average slope, the greater the number of steps, the greater the resilience of allowance revenue to potential changes in allowance demand.

5. POLICY EXPERIENCE

The first application of price-responsive allowance supply was the adoption of an auction reserve price floor at the 2009 launch of the Regional Greenhouse Gas Initiative, which currently covers the electricity sector in 12 northeastern US states. RGGI also offers a quantity of allowances in addition to the anticipated emissions cap at a cost containment reserve price step. The Western Climate Initiative CO_2 economy-wide trading program comprising California and Quebec also has a price floor and offers allowances in addition to the anticipated cap in a two-step allowance price containment reserve. In addition, it has a price ceiling at which an unlimited supply of compliance instruments (i.e., allowances) become available. In both these programs, the price floor has been periodically triggered automatically constraining the number of allowances that are sold in the auction, and in both programs the price has also risen off the price floor in subsequent auctions. In RGGI, the cost containment reserve has been triggered twice.

In addition to these automatic adjustment mechanisms, both programs have administered reductions in allowance supply during regularly scheduled program reviews. This

33. Under this discrete formulation, the differences in revenue vary inconsistently and to a diminishing degree when comparing supply curves with greater than one step.

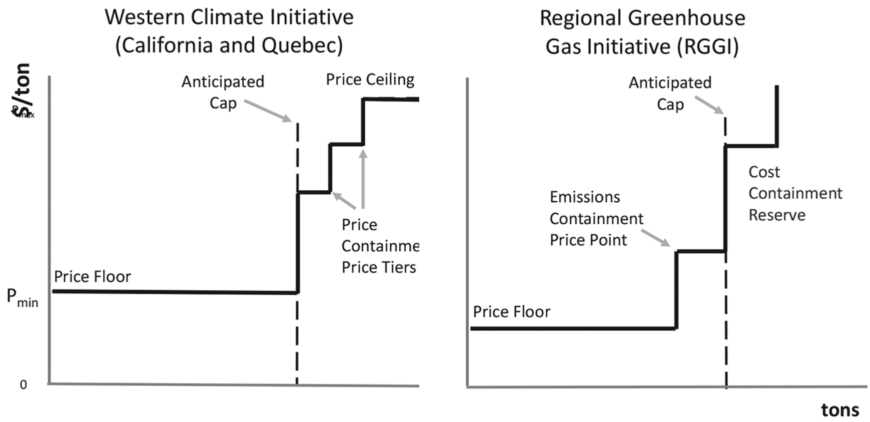

Figure 7. Actual price-responsive supply schedules

approach has been especially important in RGGI, where in 2012 the price had rested on the price floor for 11 consecutive auctions coincident with the accumulation of a large bank of unused allowances. When a large bank accumulated again three years later, RGGI again reduced allowance supply.

These programs originally unfolded in the face of several uncertainties that primarily resolved to depress emissions and the demand for allowances. The expansion of natural gas supply has contributed to reduced coal-fired generation. The economic recession in 2008–9 reduced electricity demand, which remained low as the economy recovered. State and federal policies to support renewable technologies put downward pressure on emissions allowance prices, as have programs to promote energy efficiency in buildings and vehicles. A large portion of the auction proceeds in both trading programs is explicitly directed toward strategic energy investments to accelerate emissions reductions.

RGGI has been especially affected by the policy ambitions for emissions reductions of many of its member states that collectively exceed the regional goal.[34] To avoid a waterbed effect that might result from state-level ambitions, RGGI adopted a new automatic adjustment feature, known as the emissions containment reserve, to provide additional price responsiveness in the allowance supply curve taking effect in 2021, which applies a reserve

34. Modeling exercises for RGGI in 2016 using the Integrated Planning Model (IPM) anticipated a price path rising from $7 to $9 between 2020 and 2026 (https://www.rggi.org/program-overview-and-design/design-archive/2016-materials). By April 2017, due to changes natural gas price forecasts, updated projections for electricity demand and the cost and performance of renewables, and anticipation of state policies and additional renewable imports from Canada, IPM's projected allowance price for 2020 and the subsequent decade fell to just above $2.

price above the price floor level to 10% of the allowances offered in the auction.[35] Consequently, we observe that the two North American carbon markets show an evolving transition in emissions trading away from inelastic allowance supply that has framed the debate over prices versus quantities for nearly 50 years, toward increasing price responsiveness of allowance supply. A schematic of the allowance supply schedules in these programs is shown in figure 7.

6. CONCLUSION

A key challenge for policy makers in implementing emissions pricing schemes is how best to introduce policy flexibility and to update regulatory stringency as new information arises about marginal abatement costs, broadly defined. We propose a practical strategy for implementing a mechanism first proposed by Roberts and Spence (1976), which effectively eliminates the distinction between price and quantity instruments for controlling emissions. Roberts and Spence proposed a sequence of markets, each with its own price collar. Until now, this strategy has not been thought practical, since each of the small asset markets would be too thin for competitive price discovery. Our strategy, price-responsive supply, determines price and quantity simultaneously by using the policy maker's best estimate of the marginal damage schedule as the supply function that is used to settle allowance auctions. We show theoretically that this mechanism, if implemented in a competitive auction, dominates a pure price mechanism even in cases that previously have appeared to favor a price mechanism over emission trading.

The key advantage of price-responsive supply is that it automatically adjusts the supply of allowances contemporaneous with the formation of the market price and, hence, contemporaneous with the discovery of new information by market participants. A price-responsive allowance supply supports a dynamic process that enables policy makers to use incentive-based regulation to achieve environmental quality goals with regulations that interact positively with companion efforts to achieve multiple, related policy objectives. Price-responsive supply also helps overcome the waterbed effect and establishes a predictable framework for policy updating that can reduce regulatory risk.

We have argued here that, with a price-responsive allowance supply that automatically adjusts to new information about abatement costs, emissions markets are preferable to a feasible emissions charge, including a charge that is updated over time. Our experiments demonstrate that price-responsive supply can be implemented through the auctions currently used in existing emissions markets and that it can reduce price and revenue volatility. Both RGGI and the Western Climate Initiative have made initial steps toward implementing elements of price-responsive supply, which have been important to the success of these cap-and-trade programs.

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35. Washington (state), which passed legislation in 2021 to enact an economy-wide CO_2 trading program beginning in 2023, also includes an emissions containment reserve.

We test the price-responsive supply mechanism in the laboratory setting. In multiround sessions, during each round subjects purchased allowances in a uniform price, sealed bid auction and then banked allowances or used them for current compliance. We found that the presence of the price-responsive supply schedule as the auction settlement rule has an early and persistent effect on allowance price and reduces price variability. We also found evidence that reduced variability in prices led to reduced variability in auction revenues, at least with a linear price-responsive supply schedule. We find suggestive evidence of reduced banking of allowances, at least in early periods.

Even if policy makers embrace the efficiency advantage of moving away from inelastic (fixed) allowance supply, they face a challenge in identifying the marginal damage schedule that would enable them to set an efficient supply schedule. They are faced, nonetheless, with the practical challenge of implementing emissions pricing and a specific challenge in the variability of auction proceeds, which are important to program-related investments. We explore the performance of price-responsive allowance supply in simulation modeling of CO_2 emissions reduction to develop policy guidance. Where demand for emissions allowances is inelastic, we find that a flatter allowance supply schedule has less revenue variability when demand for allowances falls below expected levels. For any given slope in an allowance supply schedule, we find that more price steps will reduce revenue variability.

Our results have particular relevance for efforts to control global warming. Climate policy is taking shape in international, national, and subnational contexts where the balancing of economic and political costs and benefits is part of a regulatory negotiation within and between jurisdictions. National and subnational environmental goals are derived and evolve in a noncooperative coordination setting with substantial uncertainty. Most jurisdictions that have adopted carbon pricing have chosen a cap-and-trade approach, with emissions targets that are clearly not globally optimal and are not static. The inherent flexibility of the price-responsive supply mechanism may facilitate the wider adoption of carbon pricing globally.

Price-responsive supply contributes to a resolution of the difficult choice between price versus quantity instruments that has characterized nearly 50 years of economic debate. Such a schedule moves toward a design for environmental markets that more closely resembles that of other commodities. We anticipate that price-responsive supply can help reduce the costs of administrative adjustments to program stringency, making the policy more durable and helping to increase the influence of emissions pricing in driving emissions reductions moving forward.

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