Bankability and Information in Pollution Policy

Garth Heutel

Abstract: I assess the role of bankability and information in environmental policy design. I develop a model demonstrating that banking and borrowing can be allowed for a price policy as well as a quantity policy. I compare expected welfare between price and quantity policies, with and without banking, under several different scenarios regarding uncertainty and information. A bankable policy can provide an efficiency improvement by allowing for smoothing of costs, though it is not necessarily more efficient than a policy that does not allow banking. The ranking of prices versus quantities and of bankability versus nonbankability depends on both the slopes of marginal costs and benefits and on the specification of uncertainty and information.

JEL Codes: D62, H23, Q54, Q58

Keywords: Prices vs. Quantities, Pollution Tax, Pollution Cap

UNDER PERFECT INFORMATION, an externality market failure can be efficiently solved using either a price or a quantity instrument. For example, pollution can be reduced to its efficient level through either a pollution tax or a cap-and-trade scheme. Under certain types of information asymmetry, the equivalence between price and quantity instruments breaks down (Weitzman 1974). Researchers have argued that an advantage of quantity instruments over price instruments is that quantity instruments are bankable (Fell et al. 2012; Pizer and Prest 2020). For example, pollution permits in a cap-and-trade scheme can be banked for future use if abatement costs are lower than expected in the current period. Many real-world tradable pollution permit markets, like the Regional Greenhouse Gas Initiative and the European Union Emissions Trading Scheme, allow for banking or borrowing (Chevallier 2012).

Several papers that extend the framework of Weitzman (1974) consider the use of banking and borrowing of permits and its effect on efficiency. Fell et al. (2012)

Garth Heutel is at Georgia State University and the National Bureau of Economic Research (gheutel@gsu.edu). Thanks to Stephen Holland, Billy Pizer, Marty Weitzman, and seminar participants at Georgia State University and Georgia Tech for comments, and to Puneet Arora and Wenwen Li for research assistance.

Received February 27, 2019; Accepted March 10, 2020; Published online June 2, 2020.

JAERE, volume 7, number 4. 2333-5955/2020/0704-0006$10.00 https://doi.org/10.1086/708908

evaluate the welfare effects of allowing limited banking and borrowing, and they numerically simulate to find that allowing for banking and borrowing can make a quantity policy nearly as effective as a price policy. Williams (2002) argues that banking is optimal for stock but not flow pollutants. Kollenberg and Taschini (2016) model a policy in which policy makers update the emissions cap in response to the number of permits in the bank to reduce costs. Most closely related to this study are two papers that use two-period models to study the efficiency of allowing banking. Pizer and Prest (2020) show that banking can improve efficiency and in some cases achieve the first best; by contrast Weitzman (2020) shows that banking is always dominated by either nonbankable quantities or nonbankable prices.

This paper makes two main contributions. The first is that the paper considers another policy option that has until now been ignored by policy modelers: what I call *bankable prices*. Intertemporal trading can be built into a price (tax) policy as well as into a quantity (permit) policy. With bankable prices, the firm is given a price in each period but can choose to defer payment for its actual output or emissions until the future. Alternatively, the firm can accelerate payment for future emissions at the current price with no restrictions.[1] In short, the firm has the option of deferring or accelerating its tax liability. This policy option is similar to other real-world policies that exist in other tax contexts, but it has not yet been applied to environmental taxes. I develop a model allowing for bankable prices, and I compare that policy to three other policies: bankable quantities, nonbankable quantities, and nonbankable prices. Under several different scenarios regarding the correlation of shocks across time and the ability of the planner to observe those shocks, I provide expressions (analogous to the well-known result from Weitzman [1974]) for the expected welfare difference between one policy and another.

The second main contribution of the paper is to assess and clarify an existing literature in a cohesive, unified framework. Even if one questions the practical relevance or feasibility of a bankable price policy, by modeling it and comparing it to the other policy options, we learn something about the prior literature's welfare comparisons between these other policies. I identify and clarify the value of bankability and its distinction from the relative values of price versus quantities, which are muddled together in the prior literature that does not separate the option of bankability from the choice between prices and quantities. I also assess the important role of the information structure of the model, in particular how much is known by the policy maker and when. This paper thus provides conceptual completeness bridging the existing literature.

This study is the first to my knowledge that models bankable prices. It follows closely from the models in Pizer and Prest (2020) and Weitzman (2020), both of which compare nonbankable prices, nonbankable quantities, and bankable quantities,

1. What I refer to as a "bankable" policy is actually both bankable and borrowable; for conciseness I will just use the term "bankable."

but omit bankable prices.[2] Like Pizer and Prest (2020), this model allows for policy updating: the planner can observe the first-period shocks before the second period and adjust its policy in response. Like Weitzman (2020), this model allows for shocks that differ across time but are correlated. By allowing for both of these features, this model helps resolve the somewhat contradictory results from those two papers, in addition to its contribution of modeling bankable prices.

The real-world relevance of studying bankable prices is questionable: is a bankable price policy feasible? Bankable quantity policies have been proven feasible, since most existing cap-and-trade markets have some provisions for intertemporal trading.[3] I am not aware of any emissions tax policies that offer any form of intertemporal trading. However, some forms of intertemporal trading are allowed for other types of taxes. In the appendix (available online), I describe in detail several real-world tax policies that exhibit this feature, including individual retirement accounts and a tax loss carryforward. None of these policies exactly mimic the bankable emissions price policy modeled here, and I discuss their similarities and differences in the appendix. Given that bankability is present in emissions quantity policies and in some other tax policies, the prospect of bankability being incorporated into emissions tax policies seems reasonable.

I find that the advantage of bankable prices depends on whether the planner can observe the shocks and whether the shocks differ across periods. In the simplest scenario where the shocks are identical across periods and the planner never observes them, bankability offers no advantage to either a price or a quantity policy. When the planner observes the shocks after the first period so policy updating is possible, bankability offers an advantage (in fact, it allows the planner to achieve the first best). But, the advantage is identical for either a bankable price or a bankable quantity policy; and thus bankability does not uniquely confer an advantage upon quantity instruments. When the shocks differ across the two periods and are correlated, but the planner never observes them, then bankability does not offer any advantage for a price policy. Finally, in the most complete scenario when the shocks differ across periods and the planner can update policy after observing the first-period shocks, the advantage of bankability is more complicated and cannot a priori be signed. Whenever prices dominate quantities, then bankability dominates nonbankability. However, when quantities dominate prices, then bankability may or may not dominate nonbankability. The comparison between a bankable quantity policy and a nonbankable quantity policy identifies one term in the welfare formulation in which nonbankable quantities dominate if marginal costs are steeper than marginal benefits, as identified in Weitzman (2020). But in addition to this term, there is a term that represents an unambiguous advantage of bankability, regardless of

2. Gerlagh and Wan (2018) is another recent working paper comparing these three policies.

3. See table 1 in Hasegawa and Salant (2014)—all six policies presented offer some form of banking or borrowing.

the slope of marginal cost or benefit curves. This represents the fact that the firm can smooth its production over time in the face of the shock value that it observes.

Finally, I provide a back-of-the-envelope numerical simulation exercise to gauge the magnitude of the efficiency differences across policies when applied to global climate change policy. Under the base-case parameter values, the bankable price policy dominates all other policies, and the efficiency gain of moving from a nonbankable price policy to a bankable price policy is about one-tenth of the efficiency gain from moving from a quantity policy to a price policy. Under other parameterizations, the efficiency gain of bankability can exceed the efficiency gain of a price policy over a quantity policy.

The following section presents the model, and section 2 presents the results from four different scenarios regarding information. Then section 3 explores the implications through numerical simulations.

1. MODEL

Consider the standard specification of quadratic benefits and costs of producing some good q_t as in Weitzman (1974):

$$C(q_t, \theta_t) = c_0 + (c_1 + \theta_t)(q_t - \hat{q}) + \frac{c_2}{2}(q_t - \hat{q})^2,$$

$$B(q_t, \eta_t) = b_0 + (b_1 + \eta_t)(q_t - \hat{q}) - \frac{b_2}{2}(q_t - \hat{q})^2.$$

The good q_t can be interpreted as abatement of emissions. The random variables, θ_t and η_t, affect the first but not the second derivative of the cost and benefit functions, respectively. That is, they shift the level but not the slope of the marginal cost and marginal benefit functions. The random variables equal zero in expectation. Assume that both b_2 and c_2 are positive, so that marginal costs increase and marginal benefits decrease. Assume $c_1 = b_1$. These assumptions are equivalent to a normalization ensuring that in expectation $\hat{q}$ is the optimal quantity (Weitzman 2020). There are two time periods, $t = 1$ and $t = 2$, and I ignore discounting (i.e., set the discount factor $= 1$).

A representative firm chooses q_t in each period to minimize costs C; the firm does not consider or care about benefits B. With no policy or regulation, the firm chooses $q_t = \hat{q} - (c_1 + \theta_t)/c_2$. This assumes an interior solution and that the firm observes the shock value, both of which I assume throughout the paper.

I consider four different policies available to the planner, who always seeks to maximize expected welfare (i.e., expected net benefits) $E[B[q_1, \eta_1] - C[q_1, \theta_1] + B[q_2, \eta_2] - C[q_2, \theta_2]]$. First, the planner can set a nonbankable quantity policy $\{\tilde{q}_1, \tilde{q}_2\}$, detailing how much the firm can produce each period. Given this policy, the firm's decision is trivial: it must produce $q_t = \tilde{q}_t$ in each period.

Second, the planner can set a nonbankable price policy $\{\tilde{p}_1, \tilde{p}_2\}$, in which the firm faces a price per unit of output in each period. The firm's optimization problem in period t is

$$\max_{q_t} \tilde{p}_t q_t - C(q_t, \theta_t).$$

Third, the planner can set a bankable quantity policy, setting $\{\tilde{q}_1, \tilde{q}_2\}$ but allowing the firm to choose a quantity B to bank ($B > 0$) or borrow ($B < 0$) between the two periods. At the start of period 2, the firm would find itself with a bank B and be required to produce $q_2 = \tilde{q}_2 + B$. If $B > 0$, some of the first period's allotment $\tilde{q}_1$ was banked, so the firm can produce more than its allotment $\tilde{q}_2$. If $B < 0$, then some of the second period's allotment was borrowed back in the first period, so the firm in the second period must produce less than its allotment $\tilde{q}_2$. At the start of period 1, the firm chooses both its actual quantity produced q_1 and the amount that it banks or borrows B subject to $q_1 = \tilde{q}_1 - B$.

Fourth and finally, the planner can set a bankable price policy, setting $\{\tilde{p}_1, \tilde{p}_2\}$ but allowing the firm to choose a quantity B to bank or borrow between periods. If $B > 0$, then the firm banks some of its output to the second period and therefore faces the second-period price on that quantity. Thus, its first-period maximand is $\tilde{p}_1(q_1 - B) - C(q_1, \theta_1)$. In the second period, the firm faces the second-period price on its actual second-period output plus the banked output, so its maximand is $\tilde{p}_2(q_2 + B) - C(q_2, \theta_2)$. When $B < 0$, these maximand expressions are unchanged, though the interpretation of B is borrowing from period 2 to period 1.[4]

For each policy, I solve for the firm's optimal response. Given the firm's optimal response, I solve for the planner's optimal policy level, set to maximize expected welfare. Finally, I calculate expected welfare given the optimal policy level and optimal firm response. I compare expected welfare across the four policies to see which policy the planner would prefer ex ante.[5] I make this comparison for four different scenarios involving the specification of the shocks and realization of the uncertainty over the random variables.

Figure 1 describes the information structure and timing of the model and the differences across the four scenarios. The top panel lists the six steps of the model in chronological order, arranged into the two periods (plus a period 0). The shocks are all realized at the start of the model (which I call period 0) and immediately observed by the firm but not by the planner. In the first two scenarios (A and B), the shocks are identical across periods; in the other two scenarios, they are different though correlated (described below). The planner does not observe the shocks in the first period. In

4. The bankable price policy can also be thought of as a deferred or accelerated tax liability. I use the term "bankable price" to highlight the policy's similarity to the bankable quantity policy that has been modeled previously in the literature. See app. A.1 for a comparison of the bankable price policy to other deferred tax liability policies. For an analysis of delayed compliance timing of quantity (but not price) policies, see Holland and Moore (2013).

5. While the planner can choose which of the four policy options yields the highest expected welfare, the firm does not have the option to choose which policy it is subject to, as in Krysiak and Oberauner (2010).

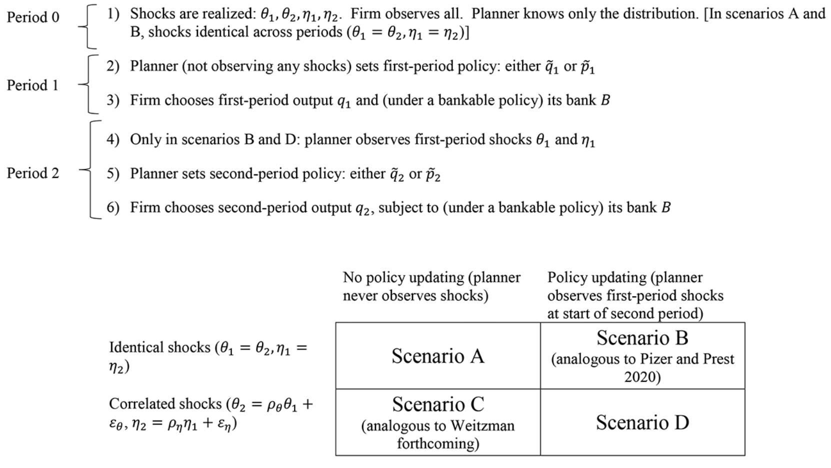

Figure 1. Timeline and information structure of model

scenarios B and D, the planner observes the first-period shock values at the start of the second period (though it never observes the second-period shock values). The bottom panel of figure 1 describes the difference across the four scenarios, which are based on whether or not the shocks are identical across periods and whether or not the planner ever observes the first-period shocks (in which case policy updating is available). As described in more detail below, scenario B roughly corresponds to (though does not exactly mimic) the base-case setup in Pizer and Prest (2020), while scenario C roughly corresponds to (though does not exactly mimic) the setup in Weitzman (2020).

Since one goal of this paper is to assess and clarify the literature, the model inherits the information structure from this literature. As in prior literature, the assumptions underlying this structure are mathematically convenient but might be questionable in reality. The firm's knowledge of all of its shock values at the outset is referred to as "super-prescience" by Weitzman (2020). Pizer and Prest (2020) interpret the information structure as one of a difference in timing rather than deep uncertainty: where the planner learns about the shocks when the firms do but cannot act until later, perhaps due to the bureaucratic process. The uncertainty issue in these models is a problem of asymmetric information, where the firm knows more than the government. There is room to modify these assumptions and consider alternative information structures, but the strength of this literature over the past several decades has been in gaining valuable intuition about policy issues via the simplicity of tractable models.[6]

6. Weitzman (2020, 441) addresses this point: "The emphasis in the model of this paper is on clarity of exposition and the appealing simplicity of clean, crisp analytical results. It is hoped that the model preserves enough of 'reality' to give some useful insights, if only at a fairly high level of abstraction."

2. RESULTS

I summarize the main results in table 1. For each of the four scenarios (the rows), table 1 lists the expected welfare under each of the four policy options (the columns). Each value is expressed relative to the expected welfare of nonbankable quantities in scenario A, so that the upper-left entry is set to zero.[7] In this section, I proceed through the rows of the table, discussing the results in each case. The proofs and mathematical details are relegated to the appendix, especially in the first three scenarios and for all policies other than the bankable price policy, since these cases are not new to the literature. The contributions of this paper to the literature are in the bottom row and the right-most column of table 1.[8]

2.1. Scenario A: Identical Shocks, No Policy Updating

The realizations of the random variables here are identical across the two periods; that is, $\theta_1 = \theta_2 \equiv \theta$ and $\eta_1 = \eta_2 \equiv \eta$; $E[\theta] = E[\eta] = E[\theta\eta] = 0$, and $\sigma_\theta^2 \equiv E\left[\theta^2\right]$ and $\sigma_\eta^2 \equiv E[\eta^2]$. All results are proven in appendix A.3.

First, consider the nonbankable quantity policy $\{\tilde{q}_1, \tilde{q}_2\}$. It is straightforward to show that the planner's optimal policy is to set $\tilde{q}_1 = \tilde{q}_2 = \hat{q}$. Given this policy and the firm's response to it, the expected net benefits of the nonbankable quantity policy is

$$\mathrm{EW}_{\mathrm{NBQ}}^{A} = 2(b_0 - c_0). \tag{1}$$

The acronym EW is for expected welfare (i.e., expected net benefits), the subscript NBQ indicates the nonbankable quantity policy, and the superscript A indicates scenario A.

Second, consider the nonbankable price policy $\{\tilde{p}_1, \tilde{p}_2\}$. Solving for the planner's optimal policy yields $\tilde{p}_1 = \tilde{p}_2 = c_1$ (the planner sets the price equal to the expected marginal cost). Given this optimal policy and the firm's response to it, the expected net benefits of the nonbankable price policy are

$$\mathrm{EW}_{\mathrm{NBP}}^{A} = 2(b_0 - c_0) + \frac{\sigma_\theta^2}{c_2^2}(c_2 - b_2). \tag{2}$$

Comparing this equation to equation (1), the difference in expected welfare between the nonbankable quantity policy and the nonbankable price policy is

$$\Delta_{\mathrm{NBP,NBQ}}^{A} = \frac{\sigma_\theta^2}{c_2^2}(c_2 - b_2). \tag{3}$$

7. The value of that expected welfare is $2(b_0 - c_0)$, so all of the entries in table 1 subtract that expression from the actual expected welfare.

8. The first main contribution of this paper is the introduction of bankable prices; this is the right-most column. The second main contribution is the assessment and clarification of the existing literature; this is the bottom row.

Table 1. Expected Welfare (Relative to Nonbankable Quantities, Scenario A)

	Nonbankable Quantities	Nonbankable Prices	Bankable Quantities	Bankable Prices
Scenario A: Identical shocks, no updating	0	$\frac{\sigma_\theta^2}{c_2^2}(c_2 - b_2)$	0	$\frac{\sigma_\theta^2}{c_2^2}(c_2 - b_2)$
Scenario B: Identical shocks, updating	$\frac{1}{2}\left(\frac{\sigma_\eta^2+\sigma_\theta^2}{b_2+c_2}\right)$	$\frac{1}{2}\left(\frac{\sigma_\eta^2+\sigma_\theta^2}{b_2+c_2}\right) + \frac{\sigma_\theta^2}{2c_2^2}(c_2 - b_2)$	$\left(\frac{\sigma_\eta^2+\sigma_\theta^2}{b_2+c_2}\right)$	$\left(\frac{\sigma_\eta^2+\sigma_\theta^2}{b_2+c_2}\right)$
Scenario C: Correlated shocks, no updating	0	$\frac{\sigma_\theta^2}{2c_2^2}(\rho_\theta^2 + 2)(c_2 - b_2)$	$\frac{\sigma_\theta^2}{4c_2^2}(\rho_\theta^2 - 2\rho_\theta + 2)(c_2 - b_2)$	$\frac{\sigma_\theta^2}{2c_2^2}(\rho_\theta^2 + 2)(c_2 - b_2)$
Scenario D: Correlated shocks, updating	$\frac{1}{2}\frac{\rho_\eta^2\sigma_\eta^2+\rho_\theta^2\sigma_\theta^2}{b_2+c_2}$	$\frac{1}{2}\frac{\rho_\eta^2\sigma_\eta^2+\rho_\theta^2\sigma_\theta^2}{b_2+c_2} + \frac{\sigma_\theta^2}{c_2^2}(c_2 - b_2)$	$\frac{1}{4}\frac{(1 + \rho_\eta)^2\sigma_\eta^2+(1 + \rho_\theta)^2\sigma_\theta^2}{b_2+c_2}$ $+ \frac{\sigma_\theta^2}{4c_2^2}(c_2 - b_2)(2 + \rho_\theta^2 - 2\rho_\theta)$	$\frac{1}{4}\frac{(1 + \rho_\eta)^2\sigma_\eta^2+(1 + \rho_\theta)^2\sigma_\theta^2}{b_2+c_2}$ $+ \frac{\sigma_\theta^2}{4c_2^2}((c_2 - b_2))((3 + \rho_\theta^2 - 2\rho_\theta))$

Note. This table presents the expected welfare under each policy, relative to the expected welfare under nonbankable quantities in scenario A. That is, each element in the table is the corresponding expression for EW (expected welfare) minus the term $2(b_0 - c_0)$.

Here Δ indicates the difference in expected welfare between two policies, where the subscript NBP, NBQ indicates that it is the difference between the nonbankable price and the nonbankable quantity policy (i.e., $\Delta^A_{\mathrm{NBP,NBQ}} \equiv \mathrm{EW}^A_{\mathrm{NBP}} - \mathrm{EW}^A_{\mathrm{NBQ}}$). The expression for $\Delta^A_{\mathrm{NBP,NBQ}}$ is simply the standard Weitzman (1974) prices versus quantities expression multiplied by two because this is a two-period model.

Third, consider the bankable quantity policy. As described in the appendix, the outcome under this policy will be identical to the outcome under the nonbankable quantity policy from equation (1): $\mathrm{EW}^A_{\mathrm{BQ}} = \mathrm{EW}^A_{\mathrm{NBQ}}$ and $\Delta^A_{\mathrm{NBQ,BQ}} = 0$. In this scenario, banking offers no advantage to a quantity policy. Because the cost shocks are equal across the two periods, the firm produces the same quantity in each period and does not bank.

Fourth and finally, consider the bankable price policy. The firm faces prices in each period $\tilde{p}_1$ and $\tilde{p}_2$. It can bank some of its quantity B and pay the price in the following period. Alternatively, if $B < 0$, it borrows forward some of its quantity from the second period and pays for it at the first-period price. The firm's problem thus is

$$\max_{q_1, q_2, B} \tilde{p}_1(q_1 - B) - C(q_1, \theta) + \tilde{p}_2(q_2 + B) - C(q_2, \theta)$$
$$\text{s.t. } q_1 - B \geq 0,\ q_2 + B \geq 0.$$

The nonnegativity constraints ensure that the firm cannot borrow or bank more than the total produced. Other than that, there are no restrictions on banking or borrowing. Given an arbitrary policy $\tilde{p}_1, \tilde{p}_2$, because the objective is linear in B the firm's problem has the following solution:

$$q_1 = q_2 = \hat{q} + \frac{\max\{\tilde{p}_1, \tilde{p}_2\} - c_1 - \theta}{c_2}. \tag{4}$$

For any price pair, the firm chooses to face the price in the higher-price period. (As in Weitzman [1974] and the subsequent literature, we interpret q as a good, not a bad, that is abatement rather than the quantity of emissions. A higher price p thus corresponds to a lower emissions tax.). If period 1 has the higher price, then the firm will borrow all of its quantity from the second period and pay it all in the first period. This response reflects the simple intuition that, when the firm can choose its price, it will choose the highest price that it can get. But, because the cost function is identical across periods and convex, the firm chooses to produce an equal amount in each period ($q_1 = q_2$). Given the firm's solution, the planner's optimal policy is to set the price equal to the expected marginal cost in each period, $\tilde{p}_t = c_1$ (more generally, the planner could set either period's price anything lower than c_1 and the other period's price equal to c_1, since the firm will choose to get paid the higher price). It follows that the outcome will be the same under this policy as it is under the nonbankable price policy (eq. [2]), so that $\mathrm{EW}^A_{\mathrm{BP}} = \mathrm{EW}^A_{\mathrm{NBP}}$ and $\Delta^A_{\mathrm{NBP,BP}} = 0$. Just like with the quantity policy, in scenario A banking offers no advantage to a price policy.

2.2. Scenario B: Identical Shocks, Policy Updating

Maintain the assumption that the realizations of the random variables are identical across periods. But now the planner can observe the value of θ and η at the end of period 1 and update its period 2 policy in response.[9] This construction is identical to the specification of uncertainty in the main model of Pizer and Prest (2020).[10]

The appendix solves for the expected welfare under the two nonbankable policies.

$$\mathrm{EW}^{B}_{\mathrm{NBQ}} = 2(b_0 - c_0) + \frac{1}{2}\left(\frac{\sigma^2_\eta + \sigma^2_\theta}{b_2 + c_2}\right), \tag{5}$$

$$\mathrm{EW}^{B}_{\mathrm{NBP}} = 2(b_0 - c_0) + \frac{1}{2}\left(\frac{\sigma^2_\eta + \sigma^2_\theta}{b_2 + c_2}\right) + \frac{\sigma^2_\theta}{2c_2^2}(c_2 - b_2). \tag{6}$$

Comparing these two equations yields

$$\Delta^{B}_{\mathrm{NBP,NBQ}} = \frac{\sigma^2_\theta}{2c_2^2}(c_2 - b_2). \tag{7}$$

This expression is identical to the original Weitzman (1974) prices versus quantities expression, because here the two outcomes are identical to each other in the second period, and in the first period the problem is identical to the one-period Weitzman (1974) problem.

Next is the bankable quantity policy. This policy yields the first-best outcome and results in expected welfare of

$$\mathrm{EW}^{B}_{\mathrm{BQ}} = 2(b_0 - c_0) + \left(\frac{\sigma^2_\eta + \sigma^2_\theta}{b_2 + c_2}\right). \tag{8}$$

Comparing this to equation (5) yields the difference

$$\Delta^{B}_{\mathrm{BQ,NBQ}} = \frac{1}{2}\left(\frac{\sigma^2_\eta + \sigma^2_\theta}{b_2 + c_2}\right) > 0. \tag{9}$$

Bankable quantities dominate nonbankable quantities.[11] Furthermore, comparing bankable quantities to nonbankable prices (eqs. [8] and [6]) yields

---

9. The planner can update in response to the observed values of the shocks but not in response to observing the level of the bank B as in Kollenberg and Taschini (2016).

10. Pizer and Prest (2020) also consider a multiperiod ($T > 2$) extension where the shocks differ across periods but are correlated. Their main results are based on a two-period model with identical shocks across periods. A multiperiod extension of my model is presented in the appendix.

11. Because the variances σ^2_η and σ^2_θ are strictly positive, this inequality is strict. Throughout the paper, all uses of "dominate" imply strictly higher expected welfare.

$$\Delta^{B}_{\mathrm{BQ,NBP}} = \frac{1}{2(b_2 + c_2)}\left[\sigma^2_\eta + \left[\frac{b_2}{c_2}\right]^2 \sigma^2_\theta\right] > 0. \tag{10}$$

This is the main result from Pizer and Prest (2020): bankable quantities dominate nonbankable prices under policy updating, and they achieve the first-best outcome. The intuition is that, after the planner observes the shock values, the planner can set the second-period quantity to "true up" the total $\tilde{q}_1 + \tilde{q}_2$ so that it equals the first-best level.

However, Pizer and Prest (2020) do not allow for bankable prices. The firm's response to a bankable price policy is the same as its response under scenario A:

$$q_1 = q_2 = \hat{q} + \frac{\max\{\tilde{p}_1, \tilde{p}_2\} - c_1 - \theta}{c_2}. \tag{11}$$

Given this firm response, the planner can induce the first best in both periods. In the second period, after observing the shock, it sets the price that induces the optimal outcome, $\tilde{p}_2 = c_1 + [(b_2\theta + c_2\eta)/(b_2 + c_2)]$. The first-period price can be anything arbitrarily low enough to ensure that it is always lower than the second-period price. Thus, the planner knows that the firm will face the second-period price, and it knows that by the second period it will have enough information to set that price to achieve the first-best. Therefore, the bankable price policy induces the first-best outcome $q_1 = q_2 = \hat{q} + [(\eta - \theta)/(b_2 + c_2)]$, just as the bankable quantity policy does, so that $\Delta^{B}_{\mathrm{BQ,BP}} = 0$. In contrast to the result from Pizer and Prest (2020), here quantities do not necessarily dominate prices under policy updating. They do so in the Pizer and Prest (2020) model where only quantities can be banked. But, when a price policy also allows banking, then both the price and the quantity policy are equivalent.[12]

2.3. Scenario C: Correlated Shocks, No Policy Updating

This scenario no longer allows for policy updating; the planner never observes the shocks. However, here the shocks are not identical across the two periods. Instead, they follow autoregressive processes given by:

12. The specification of uncertainty that allows for policy updating (used here in scenario B and also in scenario D) requires some assumptions that may be seen as heroic. The firm and planner are engaged in a mutual rational expectations equilibrium where each one's optimal action is contingent on a self-fulfilling expectation of the other's action. The firm knows its shock values from the start, and it knows that the planner will observe those values only after period 1. The firm knows that the planner will update optimally after period 1 and makes its decisions with that in mind. The planner anticipates the firm's decision and sets its policy with that in mind. This degree of rationality may be unrealistic to assume in a situation where real-world regulators are interacting with real-world firms.

$$\theta_2 = \rho_\theta \theta_1 + \varepsilon_\theta,$$

$$\eta_2 = \rho_\eta \eta_1 + \varepsilon_\eta.$$

The first-period shock values θ_1 and η_1 have variances σ_θ^2 and σ_η^2, respectively. The second-period innovations ε_θ and ε_η also have variances σ_θ^2 and σ_η^2, respectively, and are independent of the first-period shocks. Thus, for the planner, as in the previous scenarios, $E[\theta_1] = E[\theta_2] = E[\eta_1] = E[\eta_2] = E[\theta_l \eta_m] = 0$, and $E\left[\theta_1^2\right] = \sigma_\theta^2$, $E\left[\eta_1^2\right] = \sigma_\eta^2$. However, now $E\left[\theta_2^2\right] = \sigma_\theta^2(\rho_\theta^2 + 1)$, $E[\theta_1\theta_2] = \rho_\theta\sigma_\theta^2$, $E\left[\eta_2^2\right] = \sigma_\eta^2(\rho_\eta^2 + 1)$, $E[\eta_1\eta_2] = \rho_\eta\sigma_\eta^2$. This specification corresponds to that of Weitzman (2020).[13]

The expected welfare under the two nonbankable policies is

$$\mathrm{EW}_{\mathrm{NBQ}}^{\mathrm{C}} = 2(b_0 - c_0), \tag{12}$$

$$\mathrm{EW}_{\mathrm{NBP}}^{\mathrm{C}} = 2(b_0 - c_0) + \frac{\sigma_\theta^2}{2c_2^2}(\rho_\theta^2 + 2)(c_2 - b_2). \tag{13}$$

It follows that the advantage of nonbankable prices over nonbankable quantities is

$$\Delta_{\mathrm{NBP,NBQ}}^{\mathrm{C}} = \frac{\sigma_\theta^2}{2c_2}(\rho_\theta^2 + 2)(c_2 - b_2). \tag{14}$$

This equation is a slightly modified version of the standard Weitzman (1974) result, accounting for the two periods and the correlation of the cost shock across periods ρ_θ.

Next consider the bankable quantity policy. Now, the firm will still want to smooth output over the two periods since it is free to bank and borrow. However, it will not perfectly smooth to the point where $q_1 = q_2$, since the shocks are different across periods. Given this optimal policy by the firm, the expected welfare under this policy is

$$\mathrm{EW}_{\mathrm{BQ}}^{\mathrm{C}} = 2(b_0 - c_0) + \frac{\sigma_\theta^2}{4c_2^2}(\rho_\theta^2 - 2\rho_\theta + 2)(c_2 - b_2). \tag{15}$$

The term in parentheses $(\rho_\theta^2 - 2\rho_\theta + 2)$ is strictly positive since $0 < \rho_\theta < 1$.

As shown earlier, the advantage of nonbankable prices over nonbankable quantities is $\Delta_{\mathrm{NBP,NBQ}}^{\mathrm{C}} = (\sigma_\theta^2/c_2)(\rho_\theta^2 + 2)(c_2 - b_2)$, which is positive whenever $c_2 > b_2$, that is,

13. However, Weitzman (2020) considers a more general specification that allows for any joint distribution of the two periods' shock values. The specification here is a special case of that more general specification. The special case provides some additional intuition since the AR correlation parameters ρ_θ and ρ_η are present in the expressions. In app. A.2, I present the corresponding expressions under the more general assumptions about the shocks from Weitzman (2020) and show that they are consistent with the ones here.

marginal cost is steeper than marginal benefit. The advantage of bankable quantities over nonbankable quantities is

$$\Delta^{C}_{BQ,NBQ} = \frac{\sigma^2_\theta}{4c_2^2}(\rho^2_\theta - 2\rho_\theta + 2)(c_2 - b_2). \tag{16}$$

This expression has the same sign as $(c_2 - b_2)$, so bankable quantities dominate nonbankable quantities if and only if marginal cost is steeper than marginal benefit. This result is identical to the surprising result in Weitzman (2020; his eq. 47) that bankable quantities are not unambiguously preferred to nonbankable quantities. The explanation is that bankable quantities are unambiguously preferred on cost grounds, but not necessarily so when benefits are factored in as well (as they are in the calculation of expected welfare). The nonbankable quantity policy keeps quantity equal across periods, which is definitely not cost-effective. But, maintaining a constant quantity is welfare improving vis-à-vis benefits. When marginal benefits are steeper than marginal costs, this smoothing over benefits dominates the lack of smoothing over costs.

The advantage of bankable quantities over nonbankable prices is

$$\Delta^{C}_{BQ,NBP} = \frac{\sigma^2_\theta}{4c_2^2}(\rho^2_\theta + 2\rho_\theta + 2)(b_2 - c_2). \tag{17}$$

This difference is positive whenever $b_2 > c_2$, so bankable quantities dominate nonbankable prices if and only if marginal benefit is steeper than marginal cost. When comparing only these three policies, this yields the result that nonbankable prices dominate bankable quantities, which dominate nonbankable quantities whenever $c_2 > b_2$, and that nonbankable quantities dominate bankable quantities, which dominate nonbankable prices, whenever $c_2 < b_2$, the result found in Weitzman (2020).

Does adding the fourth policy option—bankable prices—affect that ranking? In this scenario, the answer is no, because bankable prices are equivalent to nonbankable prices.

$$EW^{C}_{BP} = 2(b_0 - c_0) + \frac{\sigma^2_\theta}{2c_2^2}(\rho^2_\theta + 2)(c_2 - b_2). \tag{18}$$

This expression is identical to the expression for EW^{C}_{NBP} in equation (13). Under either the nonbankable or bankable price policy, the planner chooses prices such that the firm faces the expected marginal cost c_1 in each period.[14] It follows that in scenario C, the addition of bankable prices does not change the ranking found earlier when just considering the three other policies. Unlike in scenario B with policy updating,

14. Under nonbankable prices, the planner chooses $\tilde{p} = c_1$ in each period; under bankable prices, the planner chooses $\tilde{p} = c_1$ in the second period, and that is the price the firm chooses to face.

here in scenario C bankability provides no advantage over nonbankability to a price policy.[15]

2.4. Scenario D: Correlated Shocks, Policy Updating

This scenario combines both the main model from Pizer and Prest (2020), which considers only policy updating, and from Weitzman (2020), which considers only correlated shocks.[16] The comparison of the two nonbankable policies (derivations in the appendix) yields

$$\mathrm{EW}^D_{\mathrm{NBQ}} = 2(b_0 - c_0) + \frac{1}{2}\frac{\rho_\eta^2\sigma_\eta^2 + \rho_\theta^2\sigma_\theta^2}{b_2 + c_2}, \tag{19}$$

$$\mathrm{EW}^D_{\mathrm{NBP}} = 2(b_0 - c_0) + \frac{1}{2}\frac{\rho_\eta^2\sigma_\eta^2 + \rho_\theta^2\sigma_\theta^2}{b_2 + c_2} + \frac{\sigma_\theta^2}{c_2^2}(c_2 - b_2). \tag{20}$$

Comparing expected welfare under the nonbankable quantity policy to expected welfare under the nonbankable price policy yields the difference

$$\Delta^D_{\mathrm{NBP,NBQ}} = \frac{\sigma_\theta^2}{c_2^2}(c_2 - b_2). \tag{21}$$

Prices dominate quantities whenever $c_2 > b_2$, as in Weitzman (1974).

Next, consider the bankable quantity policy. The appendix demonstrates how the planner updates the policy after observing the shocks, in a way that depends on the distribution of the error terms. This yields

$$\begin{aligned}\mathrm{EW}^D_{\mathrm{BQ}} = {} & 2(b_0 - c_0) + \frac{1}{4}\frac{(1 + \rho_\eta)^2\sigma_\eta^2 + (1 + \rho_\theta)^2\sigma_\theta^2}{b_2 + c_2} \\ & + \frac{\sigma_\theta^2}{4c_2^2}(c_2 - b_2)(2 + \rho_\theta^2 - 2\rho_\theta).\end{aligned} \tag{22}$$

---

15. Scenario C does not reduce to scenario A when $\rho_\theta = \rho_\eta = 1$, because the innovations in the second period (ε_θ and ε_η) prevent the two periods' shock values from being identical to each other. To nest scenario A as a special case of scenario C requires that the innovation to the second-period cost shock (ε_θ) has a different variance (say, $\sigma_{\theta 2}^2$) than the first-period cost shock has (say, $\sigma_{\theta 1}^2$), and likewise for the benefit shocks. Solutions under this alternative assumption (for both scenarios C and D) are presented in app. A.4. These alternative expressions retain all of the intuition as the results under the variance assumptions in the main model (all of the policy welfare comparisons are identical) but introduce an extra pair of variables, making the notation slightly more cluttered.

16. An extension to the model presented in Pizer and Prest (2020) with multiple periods ($T > 2$) also considers correlated shocks. I compare my results with multiple periods ($T > 2$) to that model in app. A.5

Comparing this expected welfare to that of the expected welfare under nonbankable prices yields the difference

$$\Delta^{D}_{\mathrm{BQ,NBQ}} = \frac{\sigma_\theta^2}{4c_2^2}(c_2 - b_2)(2 + \rho_\theta^2 - 2\rho_\theta) + \frac{1}{4}\frac{\sigma_\eta^2((1+\rho_\eta)^2 - 2\rho_\eta^2) + \sigma_\theta^2((1+\rho_\theta)^2 - 2\rho_\theta^2)}{b_2 + c_2}. \tag{23}$$

The first term in this expression has the same sign as $c_2 - b_2$. This term is analogous to the result found here in equation (16) and in Weitzman (2020) that bankable quantities dominate nonbankable quantities only when $c_2 > b_2$. However, there is also the second term of equation (23), which is positive. This second term captures the fact that there is an advantage of bankability, regardless of the slopes of the marginal cost and marginal benefit curves, since the firm (which has more information than the planner) can smooth out the shocks and reduce costs with bankability. This term is missing in the model from Weitzman (2020) since that model does not consider policy updating.

Finally, consider the bankable price policy. As in scenario C, the firm's optimal response to a policy is $q_1 = \hat{q} + [(\max\{\tilde{p}_1, \tilde{p}_2\} - c_1 - \theta_1)/c_2]$; $q_2 = \hat{q} + [(\max\{\tilde{p}_1, \tilde{p}_2\} - c_1 - \theta_2)/c_2]$. The planner's problem is similar to its problem under the bankable quantity policy—since it observes the first-period shock values before the start of the second period, it can set its first-period price arbitrarily low so that the second-period price is always binding, and therefore it can set this price to maximize expected welfare conditional on observing the first-period shock values.

Ex ante expected welfare is

$$\mathrm{EW}^{D}_{\mathrm{BP}} = 2(b_0 - c_0) + \frac{1}{4}\frac{(1+\rho_\eta)^2\sigma_\eta^2 + (1+\rho_\theta)^2\sigma_\theta^2}{b_2 + c_2} + \frac{\sigma_\theta^2}{4c_2^2}(c_2 - b_2)(3 + \rho_\theta^2 - 2\rho_\theta). \tag{24}$$

The second term is positive (and is identical to a term in the expression for $\mathrm{EW}^{D}_{\mathrm{BQ}}$), and the third term has the same sign as $c_2 - b_2$ (since $3 + \rho_\theta^2 - 2\rho_\theta > 0$). This expression can be compared with both $\mathrm{EW}^{D}_{\mathrm{NBP}}$, to see to the advantage that bankability offers to prices, and with $\mathrm{EW}^{D}_{\mathrm{BQ}}$, to see the advantage that prices have over quantities when both are bankable. First,

$$\Delta^{D}_{\mathrm{BP,NBP}} = \frac{\sigma_\theta^2}{4c_2^2}(c_2 - b_2)(-1 + \rho_\theta^2 - 2\rho_\theta) + \frac{1}{4}\frac{\sigma_\eta^2((1+\rho_\eta)^2 - 2\rho_\eta^2) + \sigma_\theta^2((1+\rho_\theta)^2 - 2\rho_\theta^2)}{b_2 + c_2}. \tag{25}$$

The first term has the opposite sign as $c_2 - b_2$. Compare that to the first term in equation (23), which has the same sign as $c_2 - b_2$. These terms represent the same effect, which goes in opposite directions for bankable prices and bankable quantities. When marginal cost is steeper than marginal benefit, there is an effect that yields an advantage to bankability for quantity policies. This same effect yields an advantage to nonbankability over bankability for quantity when marginal benefit is steeper than marginal cost. This is the effect identified in Weitzman (2020). But for price policies, this effect works in the opposite direction. When marginal cost is steeper than marginal benefit, nonbankability is preferred to bankability for price policies, and when marginal benefit is steeper than marginal cost, bankability is preferred.

The explanation for this, just like the explanation for the first term in equation (23), lies in the trade-off between achieving cost-effectiveness and achieving "benefit-effectiveness," or smoothing between periods so that marginal benefits are equal. For a quantity policy, making it bankable ensures cost-effectiveness since firms will smooth to minimize costs, but this may come at a cost of reducing benefits. For a price policy, making it bankable ensures that the firm faces the same price in each period, which is not necessarily cost-effective since the cost shocks vary across the two periods. But, relative to nonbankable prices, it forces the firm to internalize benefits more efficiently. Thus, when marginal benefits are steeper and internalizing these benefits is relatively more important, bankability dominates nonbankability for prices.

In addition to that effect, there is another effect, captured in the second term in equation (25), and also in the second term in equation (23), that is unambiguously positive, so that it yields an advantage to bankability regardless of the relative slopes, for either quantities or prices. This term is absent in Weitzman (2020) and is due to policy updating—the planner's ability to do so allows the firm to more cost-effectively smooth output over the two periods than it otherwise would have.

Equation (25) demonstrates that when $c_2 > b_2$ there are two offsetting effects in the ranking of bankable versus nonbankable prices. The first term is negative and the second term is positive. However, the first term is always dominated by the second term so that the sign of $\Delta^D_{\mathrm{BP,NBP}}$ is always positive. Equation (25) can be rearranged to yield

$$\Delta^D_{\mathrm{BP,NBP}} = \frac{\sigma_\theta^2 b_2^2}{4c_2^2(b_2 + c_2)}(1 - \rho_\theta^2 + 2\rho_\theta) + \frac{1}{4}\frac{\sigma_\eta^2((1 + \rho_\eta)^2 - 2\rho_\eta^2)}{b_2 + c_2}. \tag{26}$$

All terms in equation (26) are unambiguously positive. Thus there is an important distinction between the advantage that bankability offers to price policies and the advantage that it offers to quantity policies. Bankability is unambiguously preferred for price policies, but sometimes nonbankability can dominate bankability for quantity policies, as shown in equation (23). Later, in the numerical simulations, I verify this claim by finding parameter values that make it true.

Next,

$$\Delta^D_{\mathrm{BP,BQ}} = \frac{\sigma^2_\theta}{4c_2^2}(c_2 - b_2). \tag{27}$$

This expression has the same sign as $c_2 - b_2$. Just as in the original Weitzman (1974) model, prices dominate quantities whenever marginal cost is steeper than marginal benefit; this holds even when both prices and quantities are bankable, and even when shocks are correlated and policy updating is available.[17]

Comparing all four policy options in scenario D allows me to make the following claim, which summarizes the results from this scenario. When $c_2 > b_2$, then nonbankable prices dominate nonbankable quantities (from $\Delta^D_{\mathrm{NBP,NBQ}}$, the standard Weitzman [1974] result), bankable prices dominate bankable quantities (from $\Delta^D_{\mathrm{BP,BQ}}$), and bankable prices dominate nonbankable prices (from $\Delta^D_{\mathrm{BP,NBP}}$ in eq. [26]). When $c_2 < b_2$, then nonbankable quantities dominate nonbankable prices, bankable quantities dominate bankable prices, but the advantage of bankable quantities over nonbankable quantities is ambiguous (from $\Delta^D_{\mathrm{BQ,NBQ}}$). That is, quantities unambiguously dominate prices, but whether bankability dominates nonbankability depends upon the parameter values.

3. SIMULATIONS

I provide numerical simulations of the analytical results presented from scenario D to assist in the interpretation of the effects that have been identified. Several parameter values are taken from the previous literature when applying the model to the case of regulating carbon dioxide to combat climate change. From Pizer and Prest (2020), I set the marginal benefit slope $b_2 = 0$ \$/ton^2 and the marginal cost slope $c_2 = 1.6 \times 10^{-7}$ \$/ton^2. Pizer and Prest (2020) use 56(\$/ton)^2 as the variance of the benefit shock σ^2_η. For the variance of the cost shock σ^2_θ, I use 169(\$/ton)^2, which was used by Newell and Pizer (2003). Finally, Newell and Pizer (2003) set the persistence of the cost shock $\rho_\theta = 0.8$. All of these parameter values are the base-case values. I could not find a source for the persistence of the benefit shock ρ_η, which is absent in Newell and Pizer's (2003) model.

Regardless of the value of ρ_η, at these base-case values the results from scenario D demonstrate that a bankable price policy always dominates the other three policies. Because $c_2 > b_2$, prices dominate quantities, and equation (26) demonstrates that bankable prices always dominate nonbankable prices. I use equation (26) (or eq. [25]) to

17. The benefits to updating can be seen by comparing the corresponding entries in table 1 under scenarios C and D. In particular, when the shocks are independent ($\rho_\theta = \rho_\eta = 0$), then $\mathrm{EW}^C_{\mathrm{NBQ}} = \mathrm{EW}^D_{\mathrm{NBQ}}$ and $\mathrm{EW}^C_{\mathrm{NBP}} = \mathrm{EW}^D_{\mathrm{NBP}}$, so that there is no advantage to updating for either nonbankable policy. However, when the shocks are independent, then $\mathrm{EW}^D_{\mathrm{BQ}} > \mathrm{EW}^C_{\mathrm{BQ}}$ and $\mathrm{EW}^D_{\mathrm{BP}} > \mathrm{EW}^C_{\mathrm{BP}}$, so there is an advantage to updating for both bankable policies, since the planner gets to correct the first-period policy.

evaluate the dollar value of the expected gain from bankable prices relative to nonbankable prices. This value depends on ρ_η and is higher with a higher value of ρ_η. It ranges from \$88 million when $\rho_\eta = 0$ to \$175 million when $\rho_\eta = 1$. Since this is a two-period model, and that is the total expected welfare benefit over both periods, the annual welfare gain of a bankable price policy relative to a nonbankable price policy ranges from \$44 million to \$88 million. By comparison, the annual welfare gain of a nonbankable price policy relative to a nonbankable quantity policy is \$528 million (independent of ρ_η). Thus, the gain in adding bankability to a price policy is about an order of magnitude smaller than the gain in moving from a quantity to a price policy.

While this holds for the base case, for other parameter values the gain in moving from nonbankable prices to bankable prices can be even larger than the gain in moving from nonbankable quantities to nonbankable prices. For instance, when I switch the variances of the cost and benefit shock for each other compared to the base case (so that $\sigma_\eta^2 = 169\,(/\text{ton})^2$, greater than $\sigma_\theta^2 = 56\,(/\text{ton})^2$), then the annual welfare gain of a bankable price policy relative to a nonbankable price policy ranges from \$132 million to \$264 million; the annual welfare gain of a nonbankable price policy relative to a nonbankable quantity policy is \$175 million.

The base-case parameters provide an unambiguous dominance of bankable prices, so I consider an alternate parameterization in which this is not so. I assume that all the parameters are identical to the base case except that I allow the marginal benefit slope b_2 to vary from 0 (the base case) to 3.2×10^{-7} \$/ton^2, which is twice the marginal cost slope c_2 (ensuring a region where prices dominate and a region where quantities dominate). I also allow the persistence of the benefit shock ρ_η, for which there is no base-case value, to vary from 0 to 1.

Figure 2 presents simulation results from this alternative parameterization. The two parameters ρ_η and b_2 are varied along the two dimensions. The figure displays which of the policy options dominates: red when bankable prices dominate, blue when bankable quantities dominate, and green when nonbankable quantities dominate.

Whenever $b_2 < c_2 = 1.6 \times 10^{-7}$ \$/ton^2, bankable prices strictly dominate. When $b_2 > c_2$, quantities dominate prices, but the ranking between bankable and nonbankable quantities can vary. In fact, the figure demonstrates that nonbankable quantities dominate only for the highest values of b_2 (at least 2.88×10^{-7} \$/ton^2, almost double c_2). This result corresponds to the fact that the second term in equation (23) is strictly positive so must be kept small in magnitude for nonbankable quantities to dominate.

4. CONCLUSION

I extend the literature comparing price and quantity environmental policies, focusing on the role of bankability and information. I introduce a bankable price policy; the advantage that bankability offers to a quantity policy can also be extended to a price policy. Whether or not bankability offers an advantage depends on the relative slopes

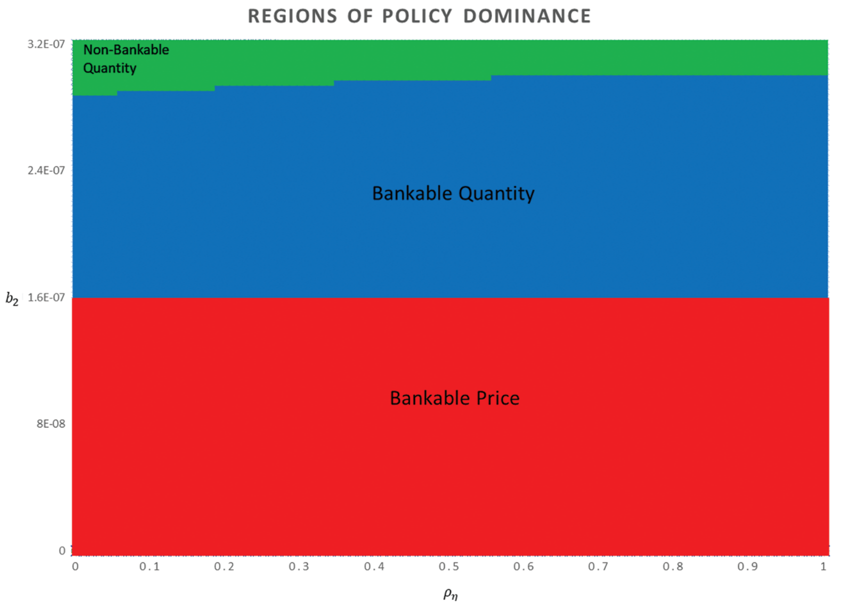

Figure 2. Policy simulations. This picture displays which of the four policy options dominates for each value of $\rho_\eta \in [0, 1]$ and $b_2 \in [0, 3.2 \times 10^{-7}]$. All other parameter values are kept at the base case values described in the text.

of the marginal cost and benefit curves, on the correlation across periods between the shock values, and on the information available to the planner. All else equal, bankability tends to offer an advantage, but that advantage may be dominated by another effect favoring nonbankability.

The model demonstrates that the advantage afforded by banking is not unique to quantity instruments, and it clarifies several seemingly disparate results from the prior literature. Like the prior literature, the model relies on many simplifying assumptions to present its results in a tractable and intuitive manner. Many of these assumptions can be modified in future research to see how results are affected. For example, the social benefit of the output can be a stock rather than a flow, as would be the case for a stock pollutant like carbon dioxide.[18] Policy makers may be allowed to modify the trading ratio between periods or be allowed to set nonlinear policies. The model could be extended to consider policies that combine a price and quantity instrument (Burtraw et al. 2018) or political economy frictions (Weitzman 2017). The model here does not incorporate moral hazard or strategic misreporting by the firm.[19]

18. See, e.g., Hoel and Karp (2002) or Pizer (2002).

19. With policy updating the planner observes the shock values themselves, not merely the firm's decision. See Ireland (1977) for discussion of this issue.

As described earlier, the information structure of this paper is inherited from the literature. It implies that the firm has "super-prescient" knowledge, by observing all of the shock values at the initial stage and thus being able to perfectly anticipate the planner's policies in both periods. This assumption is perhaps especially troubling given the assumption of a single representative firm. In reality, with multiple firms with heterogeneous costs, it seems even less realistic to assume perfect knowledge among them.[20] One could include uncertainty on the firm's part—for example, the firm might only observe its second-period shock values after the first period.[21]

Despite these simplifying assumptions, the model provides valuable intuition around environmental policy design and the potential advantages of prices versus quantities when banking may be available. The policy implications of introducing and analyzing a bankable price policy are clear—I identify cases in which allowing bankable prices can be welfare improving. While no real-world emissions price policy currently features banking, it is feasible that a provision for bankability could be worked into one in the future. This paper demonstrates when it would be efficient to do so.

REFERENCES

Ambec, Stefan, and Jessica Coria. 2013. Prices vs. quantities with multiple pollutants. *Journal of Environmental Economics and Management* 66 (1): 123–40.

Burtraw, Dallas, Charlie Holt, Karen Palmer, Anthony Paul, and William Shobe. 2018. Quantities with prices. RFF Working paper 18-08, Resources for the Future, Washington, DC.

Chevallier, Julien. 2012. Banking and borrowing in the EU ETS: A review of economic modelling, current provisions and prospects for future design. *Journal of Economic Surveys* 26 (1): 157–76.

Fell, Harrison, Ian A. MacKenzie, and William A. Pizer. 2012. Prices versus quantities versus bankable quantities. *Resource and Energy Economics* 34 (4): 607–23.

Gerlagh, Reyer, and Roweno J. R. K. Wan. 2018. Optimal stabilization in an emission permits market. CESifo Working paper series no. 6950, Center for Economic Studies and ifo Institute for Economic Research, Munich..

Hasegawa, Makoto, and Stephen Salant. 2014. Cap-and-trade programs under delayed compliance: Consequences of interim injections of permits. *Journal of Public Economics* 119:24–34.

Hoel, Michael, and Larry Karp. 2002. Taxes versus quotas for a stock pollutant. *Resource and Energy Economics* 24 (4): 367–84.

Holland, Stephen P., and Michael R. Moore. 2013. Market design in cap and trade programs: Permit validity and compliance timing. *Journal of Environmental Economics and Management* 66 (3): 671–87.

Ireland, Norman J. 1977. Ideal prices vs. prices vs. quantities. *Review of Economic Studies* 44 (1): 183–86.

Karp, Gordon, and Gary W. Yohe. 1979. The optimal linear alternative to price and quantity controls in the multifirm case. *Journal of Comparative Economics* 3 (1): 56–65.

20. Several other papers have extended this framework to consider multiple firms (e.g., Karp and Yohe 1979) or multiple pollutants (e.g., Ambec and Coria 2013).

21. See Gerlagh and Wan (2018) or the multiperiod ($T > 2$) extension in Pizer and Prest (2020).

Kollenberg, Sascha, and Luca Taschini. 2016. Emissions trading systems with cap adjustments. *Journal of Environmental Economics and Management* 80:20–36.

Krysiak, Frank C., and Iris Maria Oberauner. 2010. Environmental policy à la carte: Letting firms choose their regulation. *Journal of Environmental Economics and Management* 60 (3): 221–32.

Newell, Richard G., and William A. Pizer. 2003. Regulating stock externalities under uncertainty. *Journal of Environmental Economics and Management* 45 (2): 416–32.

Pizer, William A. 2002. Combining price and quantity controls to mitigate global climate change. *Journal of Public Economics* 85 (3): 409–34.

Pizer, William A., and Brian Prest. 2020. Prices versus quantities with policy updating. *Journal of the Association of Environmental and Resource Economists* 7 (3): 483–518.

Weitzman, Martin L. 1974. Prices vs. quantities. *Review of Economic Studies* 41 (4): 477–91.

———. 2017. Voting on prices vs. voting on quantities in a World Climate Assembly. *Research in Economics* 71 (2): 199–211.

———. 2020. Prices or quantities can dominate banking and borrowing. *Scandinavian Journal of Economics* 122 (2): 437–63.

Williams, Roberton. 2002. Prices vs. quantities vs. tradable quantities. Working paper no. w9283, National Bureau of Economic Research, Cambridge, MA.