DISCUSSION PAPER

May 2015 ■ RFF DP 15-20

The Dynamics of Pollution Permits

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RESOURCES
FOR THE FUTURE

The Dynamics of Pollution Permits[*]

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May 14, 2015

Abstract

We review the literature on bankable emission permits which has developed over the last two decades. Most articles analyze either theoretical or simulation models. The theoretical literature considers the problem of minimizing the discounted sum of social costs and the possibility of decentralizing the solution through competitive permit markets. In some cases, authors do not explicitly consider pollution damages but instead assume that the planner's goal is to minimize the discounted social cost of reducing cumulative emissions by a given amount. In other cases, authors do not explicitly consider an emissions reduction target but assume that the goal is to minimize the discounted sum of pollution damages and abatement costs. Simulations permit evaluation of alternative government policies under uncertainty. We conclude by pointing out directions for future work.

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[*] This paper has been accepted for publication by the *Annual Review of Resource Economics*. We would like to thank Karsten Neuhoff, Richard Sandor, Andrew Stocking, and Luca Taschini for valuable discussions on permit markets and Dallas Burtraw, Harrison Fell, Stephen Holland, and Michael Moore for valuable comments on a previous draft of this survey.

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1 Introduction

Economists favor controlling pollution by taxes or marketable permits rather than by more direct means (command and control) because they regard firms as in the best position to make choices over time about how to reduce their own emissions in a way that minimizes discounted abatement costs or, equivalently, maximizes discounted profits.

Until the last two decades, most of the literature on pollution permits focussed on static models of emissions trading. Montgomery (1972) provides a thorough analysis. If the government issues (gratis or by auction) a limited number of tradable pollution permits and requires that one permit be surrendered for each unit of pollution emitted, then the government can limit aggregate pollution to whatever level it deems socially desirable. This level can be determined after considering the social damage from the pollution or specified exogenously. Not only can the government limit aggregate pollution to the level it desires but the resulting abatement will be efficient even if the ability of firms to abate is heterogeneous and unknown to the regulator. This follows since every firm has a private incentive to alter its abatement until its marginal cost of abatement equals the common per unit price of a pollution permit. Since every cost-minimizing firm would set marginal cost of abatement equal to the same number, socially optimal aggregate abatement would be achieved at least cost. Subsequent authors also credit Montgomery (1972) with the insight that the full marginal cost of abatement includes not only the added technological costs of reducing emissions (say, by scrubbers) but also the profit foregone relative to the situation where all firms are unregulated.

While most academics were refining analysis of this static case, policy-makers were extending emissions trading to intertemporal settings. Firms were allowed to "bank" permits that they did not immediately use or sell. Prior to 1996, there were few dynamic analysis of emissions trading. A noteworthy exception is the extraordinary, pioneering volume by Tietenberg (1985). He analyzes three classes of pollutants, among them uniformly mixed accumulative pollutants like SO_2 or CO_2 that accumulate over time in the atmosphere and create damage independent of where within the airshed their source is located. Tietenberg formulated as a discrete-time Kuhn-Tucker problem the minimization of discounted abatement costs over a finite horizon subject to a constraint that cumulative emissions not exceed a specified target. He then discusses less formally how this problem could be decentralized, noting that "In this market, the permits are an exhaustible resource; once used, they are withdrawn from circulation" (p.29).

Because Tietenberg's analysis of decentralizing this cost-minimization problem was informal, he did not discuss whether permits should all be allocated initially or should be distributed over time and, if the latter, whether firms should be allowed through borrowing provisions or infrequent "true-ups" to emit more than the firm's current holdings of permits; nor did he discuss whether such distribution should be done by grandfathering permits or by auction and, if the latter, whether the auctions should have reserve prices. Tietenberg did not investigate whether the efficient allocation which can be achieved under certainty has a counterpart under uncertainty nor did he consider the merits of imposing ceilings on permits prices through government sales of additional permits. Tietenberg's was the first but not the last word on the dynamics of emissions trading.

Our purpose here is to survey major contributions to the literature on the dynamics of permit trading that has evolved over the last two decades. Every cap-and-trade program that has been planned, whether implemented or ultimately shelved, has generated economic analyses of issues specific to a particular program. Such analyses are of limited applicability to other programs and we steer clear of them. Instead we focus on the body of literature with broader application.

The literature on dynamic models of permit trading can be divided into two classes. The first class analyzes theoretically either the social planning problem, the dynamic competitive equilibrium or how the latter can be used to implement the former. The second class relies on stochastic simulations to take account of important features in recent cap-and-trade programs is such as banking/borrowing, price ceiling, and price collars. We review this literature in the next two sections and then identify outstanding issues which future research should address.

2 Theory: Minimization of Discounted Social Costs

In static problems, the flow of aggregate emissions determines social damages which the regulator can reduce by restricting emissions. In dynamic problems, however, social damages may depend on the time path of emissions as well as their stock. The earliest dynamic papers disregarded the damage function and investigated how to achieve a cumulative emissions target at least discounted cost. We consider these papers first before turning to the literature that replaced the explicit abatement target with an explicit damage function.

2.1 Achieving an Emissions Reduction Goal

Cronshaw and Kruse (1996) motivate their analysis by noting that although "banking of emission rights has become an integral part of most programs which allow for some exchange of emission reduction between different sources" (p. 180), "there appears to be almost no analysis in the economics literature of a market for bankable permits" (p. 179). The exception they appear to have in mind is Tietenberg, whom they infer "assumes that all permits are issued immediately, and that in equilibrium firms will always bank permits" (p. 180).

Cronshaw and Kruse consider firms subject to environmental regulation, some of which are also subject to profit regulation. They show that if banking is permitted but firms must surrender permits at the time of their emissions (no borrowing and no delayed true-ups), the permit price will increase at no more than the rate of interest provided at least one firm is free from profit regulation. They show that firms not subject to profit regulation would be willing to bank permits only if the permit price increased at the rate of interest but firms subject to profit regulation would be willing to hold permits despite lower anticipated capital gains. Cronshaw and Kruse prove that the bankable permit system minimizes the sum of discounted abatement costs, where they follow Montgomery in defining the cost of abatement to include the profit that is foregone in complying with the environmental regulation.

Cronshaw and Kruse envision that each firm initially inherits no stock of pollution permits but receives a nonnegative exogenous endowment of permits in each period. Thus, the industry could be composed of identical firms, none of which is subject to profit regulation, and each of which receives permits only in the final period. Since there can be no banking in this case, their positive analysis establishes that the market price of permits must rise at less than the rate of interest. As for their normative analysis, they prove in general that the market achieves the cumulative emissions target over the finite horizon at least discounted cost but, as this example highlights, they do not allow their planner to choose a cumulative path of emissions that is in any period larger than the cumulative endowment of permits given to market participants.

Although Cronshaw and Kruse do not discuss this issue, it seems important to point out that a planner who was not constrained in this way could achieve the same overall emissions target at a strictly lower discounted abatement cost. Thus, if one regards the constraint they impose on the planner as artificial[1], their analysis suggests a very different conclusion: in the absence of borrowing or delayed true-ups, market efficiency may depend on the temporal distribution of permits.

Rubin (1996) reconsiders Cronshaw and Kruse's problem in a continuous-time, finite-horizon deterministic model. He does not consider firms subject to profit regulation but instead allows firms to emit in excess of their permit holding provided they repay this "borrowing" later. Borrowing can be prohibited in his model by requiring that the bank be

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[1] Time-dated endowments of goods in a dynamic competitive economy with pure exchange cannot be re-allocated by a planner; but the time profile of permit endowments is a policy choice; one may question why the planner should be bound by it.

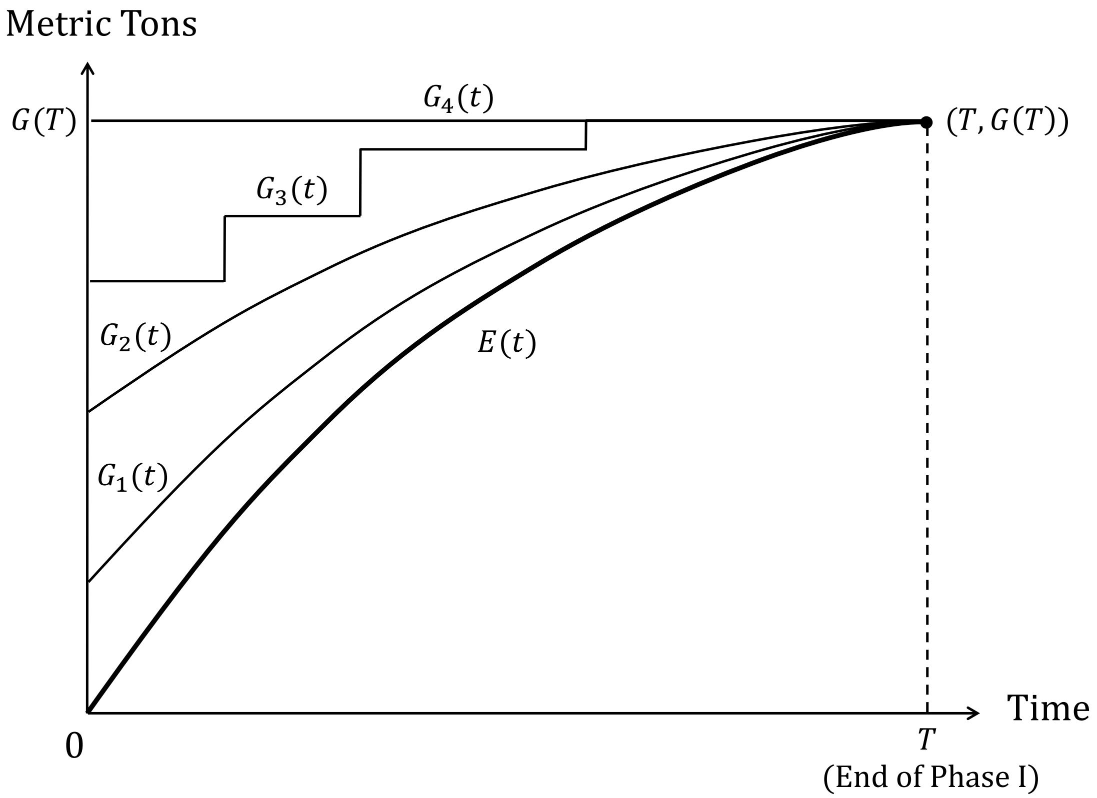
nonnegative $B_i(t) \geq 0$ for the entire finite horizon. Borrowing can be permitted by replacing this constraint with $B_i(T) \geq 0$ so that programs for which $B_i(t) < 0$ become feasible. Rubin shows that if borrowing is allowed, permit prices increase at the rate of interest (Hotelling's rule). In such a case, the market equilibrium is efficient while, if borrowing is restricted and the borrowing constraint binds, the permit price increases at less than the rate of interest. Rubin shows that in the absence of borrowing, the market can be efficient for any path of endowments if one adopts Cronshaw and Kruse's assumption, discussed above, that at every instant the planner would be subject to the same cumulative endowment constraint as the private agents.

Schennach (2000) is motivated by Title IV of the 1990 Clean Air Act Amendments (the Acid Rain Program), which allows banking but prohibits borrowing. She considers a continuous-time model of emission trading with banking (but no borrowing) over an infinite horizon. To analyze the effects of the less restrictive initial phase in of the Acid Rain Programs and the more restrictive subsequent phase, she assumes that there is an exogenous flow of permit endowments at a high rate before exogenous time T (when Phase I ends and Phase II begins) and a lower flow thereafter. In anticipation of the reduced flow of permits in Phase II, firms bank permits in Phase I and carry them into Phase II; otherwise, the reduction in permit allocations would result in an upward price jump, which cannot occur in a perfect-foresight equilibrium. Eventually, however, the banked permits carried into Phase II run out. This occurs when the permit price (and marginal cost of abatement) reach the marginal cost that can be supported by the slow flow of permits issued during Phase II.

Schennach's article is noteworthy in many respects. Her focus is positive rather than normative. She notes when analyzing the equilibrium where permits issued during Phase I are carried into Phase II that the identical equilibrium can be supported by a variety of time-varying permit allocations during Phase I; all that is required is that (1) every allocation path during Phase I distribute the same cumulative number of permits $G(T)$ and (2) whatever the time-path of permit allocations prior to the start of Phase II at time T, firms are always allocated at least as many permits as they are required to surrender in the given equilibrium before T.

Since this issue arises repeatedly, we illuminate it with a diagram. Figure 1 below plots against time the cumulative emissions of the firms ($E(t)$) in the given equilibrium and four different allocation paths for the cumulative number of permits issued by the government ($G_i(t), i = 1, \ldots, 4$). We have drawn cumulative allocation path $G_3(t)$ as a step function since auctions in fact occur periodically rather than continuously and Schennach's point is equally valid in this case as well. The slope of each (differentiable) function at time t gives the flow of permit allocations ($g_i(t)$) at time t and the flow of emissions ($e(t)$), respectively.[2] The difference equals the bank at time t : $B_i(t) = G_i(t) - E(t)$. If borrowing is prohibited and true-ups are continual (Schennnach's assumptions), then $B_i(t) \geq 0$. Hence, every permit allocation policy $G_i(t)$ that stays above $E(t)$ prior to the end of Phase I and achieves the same value $G(T)$ at the end of Phase I will generate the same competitive equilibrium. As the diagram indicates, one does not need to allocate all the permits to private agents at the outset to decentralize the solution to the social planning problem in Tietenberg (1985) if borrowing is prohibited and continual true-ups are required. Of course, if borrowing is permitted or the true-up occurs only at T, then there is no need for the bank to be positive and the only requirement is that $B_i(T) = 0$.

Figure 1: Four Paths of Permit Allocations in Phase I Resulting in the Same Competitive Equilibrium



Schennach is also the first in this literature to discuss uncertainty, mentioning both (1) the uncertainty firms face about future permit demand and (2) uncertainty about the stringency of future regulation. She even formalizes her discussion by analyzing a discrete-

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[2] That is, $\int_{x=0}^{t} e(x)dx = E(t)$, implying that $\dot{E}(t) = e(t)$ and $\int_{x=0}^{t} g_i(x)dx = G_i(t)$, implying that $\dot{G}_i(t) = g_i(t)$.

time stochastic programming problem in her Appendix D and showing how continuous-time results under uncertainty can be recovered in the limit as the length of each time period goes to zero. She is also the first author to note the connection between the dynamic emissions trading literature and the closely related commodity storage literature under uncertainty (Williams and Wright, 1991 as well as Deaton and Laroque, 1992).

Hasegawa and Salant (2014) point out that many analyses of cap-and-trade markets assume, like Schennach, that compliance is continual whereas in actual programs true-ups occur at most once a year. They investigate the properties of the equilibrium price path under "delayed compliance" and what biases are introduced if analysts ignore this important feature of the regulations.

Holland and Moore (2013) examine a broad collection of cap-and-trade programs (see Table 1),[3] identify their common structure, and then build a model taking account of that structure—an outstanding example of basing theory on detailed institutional knowledge. They construct a dynamic model of an emissions permits market under uncertainty where emission permits have different validity in terms of vintage years and permits-to-emissions compliance ratios and regulated firms face different compliance timing, prompt and delayed. They provide sufficient conditions for equilibrium abatement to be invariant to permit validity and compliance timing. The key condition for the invariance theorem is that the current price is equal to the present value of the expected prices in future periods.[4]

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[3] The table is taken from Table 1 of Holland and Moore (2013)

[4] Holland and Moore (2012) analyze the equilibrium properties in a permit market under the two overlapping compliance cycles and two overlapping permit cycles, which are specific to the Regional Clean Air Incentives Market (RECLAIM) program, and derive the invariance results similar to those proved by Holland and Moore (2013) in a more general setting.

Table 1. Compliance Timing and Permit Validity in Cap-and-Trade Programs.
Reproduced from Table 1 of Holland and Moore (2013) with their footnotes abridged.

	Compliance Timing		**Permit Banking**		**Permit Borrowing**		**Spatial Limits Within Program**
Program (pollutant)	**Emissions Reporting**[1]	**Permit True Up**	**Explicitly Allowed?** [2]	**Qualifications** [3]	**Explicitly Allowed?** [2]	**Qualifications** [3]	
Acid Rain Program (ARP)[4] (sulfur dioxide)	quarterly	annual	yes	unlimited	no	none	no
NOx Budget Program (NBP)[5] (nitrogen oxides)	quarterly	annual	yes	quantity tax on use of banked permits above a specified threshold	no	none	no
Clean Air Interstate Rule (CAIR)[6] (nitrogen oxides and sulfur dioxide)	quarterly	annual	yes	unlimited	no	none	two NO$_x$ markets in eastern U.S.
Cross-State Rule (CSAPR)[7] (nitrogen oxides and sulfur dioxide)	quarterly	annual	yes	unlimited	no	none	two NO$_x$ markets; two SO$_2$ markets; variability limits on state emissions
RECLAIM[8] (nitrogen oxides and sulfur dioxide)	quarterly	overlapping annual compliance cycles	no	limited ability to bank due to overlapping permit cycles	no	limited ability to borrow due to overlapping permit cycles	inland permits not valid in coastal zone
EU ETS[9] (greenhouse gases)	annual	annual	yes	banking not allowed from first phase to second phase	no	unlimited borrowing from the next year's vintage of permits	no
Waxman-Markey (WM)[10] (greenhouse gases)	quarterly	annual	yes	unlimited	yes	borrowing from the next year's vintage of permits; borrowing with interest from vintage years +2 to +5	no

RGGI[11] (greenhouse gases)	quarterly	3-year period	yes	unlimited	no	unlimited borrowing within 3-year compliance period	no
California AB 32 (AB 32)[12] (greenhouse gases)	annual	3-year period with 30% annual down payment	yes	unlimited	no	unlimited borrowing within 3-year compliance period conditional on annual down payment	includes electricity imported to California

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[1] This stage of program administration includes emissions reporting by regulated sources and emissions verification by the regulator.
[2] "Explicitly allowed?" asks whether the program allows banking or borrowing through an affirmative provision.
[3] "Qualifications" describes explicit or implicit conditions on banking and borrowing.
[4] The U.S. SO_2 market from Title IV of Clean Air Act.
[5] The NO_x market in the eastern U.S. known as the NOx Budget Trading Program or NBP.
[6] See Federal Register (2005).
[7] See USEPA (2011).
[8] RECLAIM is the acronym for the Regional Clean Air Incentives Market, which operates in the greater Los Angeles metropolitan area. See Holland and Moore (2012).
[9] See European Commission (2003).
[10] A legislative proposal in the U.S. Congress (H.R. 2454) to establish a U.S. CO_2 market. Waxman-Markey passed in the House. Several similar proposals in the Senate, including Kerry-Boxer and McCain-Lieberman, were never voted on.
[11] The Regional Greenhouse Gas Initiative (RGGI) is an agreement among nine states in the northeastern and mid-Atlantic region to form a regional carbon market.
[12] California's Assembly Bill 32 regulates greenhouse gases.

2.2 Accounting Explicitly for Pollution Damages

Kling and Rubin (1997) use a deterministic, continuous-time model similar to that of Rubin (1996) to evaluate social desirability of issuing a fixed number of permits and allowing firms to trade, bank, and borrow. In the first part of their paper, they show once again that under these circumstances, the competitive permit price will grow at the rate of interest (Hotelling's rule). The curve ball comes in section 2, where they take explicit account of social damages from pollution. If there are social damages, this Hotelling path of emissions—although it achieves the targeted reduction in cumulative emissions at the least discounted cost of abatement—will almost surely fail to minimize the sum of discounted abatement costs and social damages: the Hotelling path is inefficient.

In particular, Kling and Rubin assume that the social damage from pollution is a strictly increasing, weakly convex function of the contemporaneous flow of pollution. Since there is no cumulative pollution target and the damage function is independent of the stock of the pollutant, this is a static problem. In its solution, the planner should adjust abatement at each instant so that the additional cost of abating another unit equals the reduced damage from abating another unit. In the simplest case, where the marginal cost of abatement and the marginal damage function are stationary, for example, socially efficient abatement should be constant over time, not rising over time as would occur along the Hotelling path induced by cap-and-trade. Indeed, the authors suggest that, compared to no regulation, cap and trade could even be welfare reducing.

Kling and Rubin propose a clever way to decentralize this planning problem. They suggest that the regulator offer a nonzero own rate of return on permits that are banked or borrowed. If positive, this own rate of return would reward banking and penalize borrowing. Suppose for example that firms discount costs at a 5% rate of interest per year. Under Kling and Rubin's plan, a firm banking one permit in the current period would be paid back 1.05 permits a year later while a firm borrowing 1 permit in the current period would owe 1.05 permits a year later. That is, the own rate of return on permits would be 5% as well. In that case, the equilibrium price path if firms received their stock of endowments at the beginning would not be the standard Hotelling path of permit prices but a constant permit price.[5] A firm facing such a path would be indifferent whether it banked permits or sold

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[5] More generally, given the current dollar price of a permit and an r percent own rate of return on dollars in each succeeding period, one can determine the dollar price of a permit in each succeeding period if one can set the own rate of return on permits stored in each period. For example, in two periods, there will be three independent rates of exchange: the current dollar price of a permit, rate at which money today exchanges for money tomorrow, and the rate at which permits today exchange for permits tomorrow. Given these three rates of exchange, there exists only one rate of exchange between dollars tomorrow and permits tomorrow.

them since the volume of permits held by the firm (and thus their value) would be growing at the rate of interest; hence, the firm could not do better by selling its permits and banking the proceeds. Of course, even with this modified banking, an inefficient price would arise in the competitive equilibrium unless the correct number of permits is issued. Kling and Rubin warn that their proposed solution works only if the marginal damage function has a constant slope and is stationary. "The desirability of the system then depends on the degree to which social damages can be assumed to be linear and stationary" (p. 113).

Falk and Mendelsohn (1993) examine the socially optimal strategy to control stock pollutants over a finite horizon. They do not consider decentralizing the solution through trading permits in competitive markets. Since the damage function depends on the accumulated stock of pollutants rather than their contemporaneous flow, Falk and Mendelsohn's planning problem is dynamic. Additional abatement is a form of investment. It increases abatement costs in the current moment but lowers the damage from the pollutant stock over the remainder of the finite horizon. Since a unit increase in abatement today induces an exponentially declining reduction in the stock of pollutants in the future, one must discount the reduced damages not only by the rate of interest but also by the rate at which the stock of pollutants decays in the atmosphere. When applied to the case of greenhouse gases, this optimal abatement rule suggests that efficient level of abatement efforts should increase over time. Although the authors start with a simple, autonomous optimal control problem, they then take account of various real-world nonstationarities. Since this complicates their analysis, they simulate the resulting model in an attempt to compute optimal policy for controlling greenhouse gases. This requires a heroic effort to specify a damage function. The authors acknowledge the difficulty in doing this: "There is widespread agreement that the damage function is uncertain. There are very few quantitative estimates of the value of specific damages which may result from climate change. ... However, the simulations suggest that the most important uncertainties concern how things will change in the future. At what rate will potential emissions and the damage function grow over time? Will technical change lower the cost and damage function or will they remain stable over time?" (pp. 87-88). The time horizon in their simulations is 150 years. Falk and Mendelsohn do not specify a bequest function. Hence, they implicitly assume that after year 150, damages will no longer flow from the accumulated pollutant.

Biglaiser et al. (1995) consider optimal dynamic pollution regulations via permit trading (without banking or borrowing) and pollution taxes. Their model takes into account pollution-reducing investment decisions by regulated firms. The authors show that the optimal permit allocation depends on firms' pollution-reducing capital. When the regulator cannot commit to future regulation, the optimal permit regulation is time-inconsistent whereas the optimal tax policy is time-consistent.

Leiby and Rubin (2001) also take explicit account of damage from pollution. Unlike Falk and Mendelsohn, however, Leiby and Rubin not only derive a socially optimal solution to a finite-horizon, nonstationary problem but also show how to decentralize it. In addition they include a bequest function in the social planner's problem since, as they explain, "With a stock pollutant, damages do not stop at the end of the regulatory program as denoted by the end of the time horizon, T. Damages from the stock of pollution will continue until the stock pollutant decays to benign levels. The final-value term $F(S(T))$ captures the value of damages for all time periods after T (measured in period T dollars)" (p. 232). In taking account of the damage from pollutants beyond the end of the finite horizon, Leiby and Rubin modify the rule for the optimal investment in abatement derived in Falk and Mendelsohn.: "any time in the planning horizon, the socially optimal emission level is chosen such that discounted marginal abatement costs for each firm equals the present discounted value of all future marginal stock damages over the planning horizon plus the present value of marginal terminal stock damages that occur beyond the regulatory time horizon. Note that the "discount" rate used is $(\rho + \gamma)$, the financial discount rate plus the stock decay rate" (p. 240).

Leiby and Rubin's paper extends the models of Rubin (1996) and Kling and Rubin (1997) to take into account not only stock externalities in a damage function but, at the same time, flow externalities as well. As in Kling and Rubin (1997), they show that social optimality can be achieved in a competitive equilibrium if the government adjusts the own rate of return on the stock of permits banked or borrowed.

However, the authors acknowledge that their proposal of modified banking requires a large amount of information. In particular, "the environmental regulator must know the marginal damages and time rates of change in marginal damages from flows and stocks evaluated at their optimal level. This requires knowing aggregate marginal abatement costs. Of course, if the environmental regulator knew each firm's marginal abatement costs (as well as optimal marginal damages) then consistent with static analysis, permits, taxes and standards are all equivalent. ... the regulator may prefer to simply issue the optimal number of permits in each period and not allow banking and borrowing" (p. 239).

Yates and Cronshaw (2001) construct a two-period model of incomplete information where firms can bank and borrow. The regulator sets both the two-period endowment of each firm and the own rate of return at the outset without knowing the parameter of the abatement cost function of any firm in either time period. The regulator's objective is to minimize the discounted expected total social costs, the sum of abatement costs of firms plus the damages from their emissions.

Given the specific (quadratic) functional forms of the abatement cost function and the damage function, they show that, under certain conditions, allowing intertemporal trading is socially desirable if and only if the slope of the marginal damage curve is less than that of the marginal abatement cost curve. Intuitively, allowing intertemporal trading would decrease the total abatement costs while it would increase the uncertainty about the intertemporal allocation of permits by firms and thus increase the total expected damages because the damage function is convex. Therefore, as long as the expected damage from uncertain emission allocations between the two periods is not severe (the slope of the marginal damage curve is small), the regulator should allow banking and borrowing.[6]

Newell et al. (2005) consider a dynamic model of emission trading under uncertainty when banking and borrowing are allowed. They show that emissions trading can replicate the outcome of price policies if the government adjusts the own rate of return on banked or borrowed permits and can adjust the supply of permits in the last period. The own rate of return is adjusted to induce the necessary changes in permit prices and the anticipated adjustment of the supply of permits in the last period corrects the level of permit prices. Thus, the logic of their proposal is similar to those discussed by Kling and Rubin (1997) and Leiby and Rubin (2001)

3 Stochastic Simulations to Assess Government Policies

To evaluate under more realistic conditions alternative policy proposals for regulating greenhouse gases, authors have begun to simulate stochastic models. Their studies assume specific distributions of uncertainty parameters across time in abatement cost functions and simulate dynamic stochastic models using the parameter values estimated or provided by the previous literature, the U.S. Environmental Protection Agency (EPA), and the legislation bills.[7].

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[6] Feng and Zhao (2006) examine the social efficiency of intertemporal permit trading regimes under asymmetric information. In Yates and Cronshaw (2001), firms know the cost shock in each period. In Feng and Zhao (2006), each firm knows only the first-period cost shock and base their beliefs about the second-period shock on the first period realization. Like Yates and Cronshaw (2001), they conclude that that the social desirability of banking and borrowing depends on the slope of the marginal damage and abatement cost curves. Innes (2003) assumes that when a firm makes output and abatement decisions, the amount of emissions that result is uncertain. Innes finds that when intertemporal trading of permits is allowed, the first-best outcome can be achieved by appropriately setting the intertemporal trading ratio (own rate of return on banking and borrowing), the quantity of permits issued, and the schedule of fines for emission violations.

[7] The key parameter values include the slopes of the marginal cost and benefit curves, the discount rate, the initial levels of baseline emissions and the stock of emissions, the allocations of emissions permits, the interest rate on banking and borrowing, and so on

3.1 No Banking

Pizer (2002) simulates a stochastic extension of the deterministic climate-economy DICE model of Nordhaus (1994) to evaluate alternative climate policies when there is uncertainty about control costs.[8] The paper then compares a price (tax) policy and a quantity policy and also evaluates a hybrid policy, a quantity policy combined with price ceiling.[9] Pizer finds that the welfare gain from the optimal price policy is five times that from the optimal quantity policy. Moreover, he finds that a hybrid policy improves welfare compared to the pure quantity policy. Pizer (1999) and Pizer (2002) confirm that emission taxes are preferable to pure quantity controls in a dynamic setting.

Newell and Pizer (2003) develop an analytical model of policy choice for stock externality regulation and apply the resulting framework to greenhouse gas policy. In their model, the benefit function depends the accumulated stock of pollutants rather than their contemporaneous flow while the abatement costs depend on the flow of pollutants rather than their stock. They show analytically that, as Weitzman (1974) demonstrates in a static setting, price controls are preferable to quantity controls if the slope of the marginal benefit curve is flat relative to that of the marginal abatement cost. In addition to the slopes of these curves, dynamic factors including the correlation of cost shocks across time, the stock decay rate, and the rate of benefit growth also matter for the choice of policy instruments. Lower stock decay rates, greater rates of benefits growth, and greater correlation in costs across time favor quantity controls. Using simulations, they find that a price-based instrument yields several times the expected net benefits of a quantity instrument in the case of global climate change. In reaching these conclusions, they assume that there is neither banking nor borrowing of permits.

3.2 Banking

Cap-and-trade programs recently introduced or proposed in the U.S. envision the implementation of price ceiling and price floor (price collars) on emissions permits and allow intertemporal trading permits, banking and borrowing to some extent.[10]

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[8] Pizer (2002) uses the model developed by Pizer (1999), which compares the social welfare under price and quantity controls with and without uncertainty about consumer preferences and technology, where the social welfare is defined as a weighted average of the representative consumer's utility over possible states about preference parameters.

[9] The safety valve is modeled as a emissions tax with the tax rate equal to the ceiling price. This corresponds to a price ceiling implemented by sales at a fixed price from an unlimited reserve of permits. Thus as shown in Figure 6 of the paper, if the initial permit level is set at zero, the optimal hybrid policy coincides with the optimal tax policy.

[10] Jacoby and Ellerman (2004) describe the origin of a safety valve (sales of an unlimited amount of permits at a ceiling price) and policy debates on the introduction and implementation of a safety valve in a cap-

Fell and Morgenstern (2010) simulate a stochastic dynamic model of cap-and-trade programs with and without banking and borrowing. Price ceilings combined with price floors (or “price collars as they are called in the cap-and-trade literature) are assumed to increase at the rate at which the ex-ante expected permit prices increase. Each time period in their discrete-time formulation corresponds to one year. They find that price-collar mechanisms are more cost effective than both purely quantity-based and safety-valve mechanisms for the same level of expected cumulative emissions.[11] They also find that the combination of a price collar with banking and borrowing systems can achieve expected costs as low as a tax with a lower variance of emissions. They compare the net present value of abatement costs under various policies (without explicit consideration of damages or welfare).[12]

Fell et al. (2012c) simulate a stochastic dynamic model of cap-and-trade programs with banking and constrained borrowing and compare the welfare gain from the bankable quantity policy with those from price (tax) policy and non-bankable quantity policy. They find that the bankable quantity policy reduces permit price volatility, improves welfare over the non-bankable policy, and achieves the similar welfare gains under the price-based policy over the policy horizon in which the banking constraint is less likely to be binding (in the first 10–20 years in their simulation).

Fell et al. (2012b) simulate a discrete-time stochastic dynamic model of cap-and-trade programs with banking, borrowing, and price ceilings and floors. Each time period in their discrete time formulation corresponds to one year. They consider two types of price collars, soft and hard collars. With a hard collar, an unlimited supply of additional permits can be sold to defend a ceiling price; with a soft collar, the supply of additional permits available for that purpose is limited. They assume that both the floor and ceiling price increase at the rate of interest. They find that for the same level of the expected cumulative emissions, hard collars yield lower net present value of expected abatement costs than soft collars.

Fell et al. (2012a) simulate a stochastic dynamic model that is similar to the models used in other Fell’s papers but incorporates the supply of emission offsets. The supply function of offsets contain uncertainty correlated with abatement cost shocks. The simulation results show that as the uncertainty in offsets become more persistent, the expected present value

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and-trade program. Murray et al. (2009) discuss an allowance reserve in cap-and-trade programs, which implements a price ceiling by sales from a government reserve of a limited number of permits at the ceiling price. Also, see Table 1 of Holland and Moore (2013) and Hasegawa and Salant (2014) for the summary of the provisions for price control, banking and borrowing, compliance timing in cap-and-trade programs in the U.S. and EU.

[11] Burtraw et al. (2010) simulate a static model under uncertainty of cap-and-trade programs with price control mechanisms and find that a price collar (also called a “symmetric safety valve” in the paper) outperforms a safety valve in terms of welfare.

[12] To compare various policies, they set ceiling and floor prices so that expected cumulative emissions are the same.

of abatement costs (plus offset purchase costs) increases. They also show that a price collar policy is effective in reducing these costs especially with high persistence of the offset supply uncertainty and high negative correlation between the uncertainty in offset supply and the uncertainty in abatement costs.[13]

4 Future Directions

4.1 Price Floors versus Auction Reserve Prices

Many cap and trade programs seek to moderate low permit prices by imposing reserve prices on their auctions.[14] And yet, with the exception of Hasegawa and Salant (2014) and Shobe et al. (forthcoming), virtually every analysis of such programs assumes that the government instead imposes price floors.[15] Auction reserve prices and price floors are different policies and have different consequences.[16]

If the government commits to purchasing at a floor price whatever permits are offered (a "hard" price floor), then no rational seller will sell his permits for less. Hence, a hard price floor prevents the market price from ever falling below the floor. Price floors have been used in commodity agreements to prop up commodity prices (Salant, 1983; Gardner, 1979) and in exchange-rate bands to prop up foreign exchange rates. As of this writing, however, they have not been used in cap-and trade markets.[17]

If the government imposes an auction reserve price, bids below that level are disregarded. Hence, if an auction takes place when the market price is below its reserve price, nothing should sell since any potential purchaser (unless he has monopsony power) could obtain a permit for less on the permit market. Hence none of the auctioned amount would sell. An auction reserve price at most merely eliminates the sale of additional permits when the market price is already low. Shutting down a single auction, however, does not insure that

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[13] These four papers by Fell and other authors, relying on Rubin (1996), equate the market equilibrium outcome with the representative firm's cost minimization outcome. We will revisit this issue in the next section.

[14] Burtraw et al. (p. 4923, 2010) note that "the academic literature and numerous notorious examples of failed auctions point to a credible and efficient reserve price as an important aspect of auction design and refer readers to several authoritative accounts of auction design.

[15] Murray et al. (2009) and Wood and Jotzo (2011) suggest that reserve prices for auctions do not necessarily serve as a price floor or ceiling depending on the demand for permits at the time of the auctions and the number of initially grandfathered permits.

[16] Confusion between the two policies has likely been created by the common practice of referring to them by the same name. Sloppy language may have fostered sloppy thinking about these distinct policies. To avoid such confusion, we will continue to use distinct names for the two policies.

[17] Burtraw et al. (p. 4923, 2010) identify several authors as contending that price floors on permit prices can (1) induce new firms to enter, resulting in increased emissions, and (2) can discourage the adoption of new emissions-reducing technology.

the market price remains at the auction reserve price as would occur if a hard price floor were imposed instead. For example, if Europe imposed an auction reserve price of 15 euros per permit at a time when permit prices hover around 6 euros, that policy would not cause the price to jump up to 15 euros per allowance as it would if the authorities stood ready to pay 15 euros for any allowances offered.[18] For an illustration of a dynamic equilibrium in the permit market where the market price is initially below the auction reserve price, see Hasegawa-Salant, 2014 (Figure 3).

In future work, we encourage authors to incorporate reserve price policies instead of price floors in their theoretical or simulation studies of cap-and-trade policies since that is the policy in use.

4.2 Within Compliance Periods versus Between Them

No cap-and-trade program requires regulated firms to be in compliance continually. Firms are required to true-up only periodically—in some cases once per year, in other cases once every three years. With the exception of Holland and Moore (2012 and 2013) and Hasegawa and Salant (2014), however, no analyses have recognized that firms can be out of compliance within a compliance period even if borrowing is prohibited. Failure to recognize this feature of cap-and-trade programs can lead to predicted behavior that cannot in fact occur in equilibrium. For example, Schennach assumes that borrowing is prohibited at every instant because the U.S. Environmental Protection Agency (EPA) imposed a restriction "that a unit cannot borrow allowances from its allocations for future years" (p. 189). However, she also notes EPA required annual true-ups: "at the end of each year, every unit has to have enough allowances in its 'account' to cover its SO_2 emissions for the year." Although borrowing was prohibited, the requirement in the program that firms true-up only once per year also allowed them to be out of compliance between true-ups. This is equivalent to allowing borrowing within the compliance period.

In Figure 2, we depict the equilibrium price path predicted by Schennach as rising at the rate of interest during Phase I and the first part of Phase II and then remaining flat from τ onward. Schennach assumed that EPA required continual compliance and that the government auctioned permits during Phase II at a constant rate (smaller than during Phase

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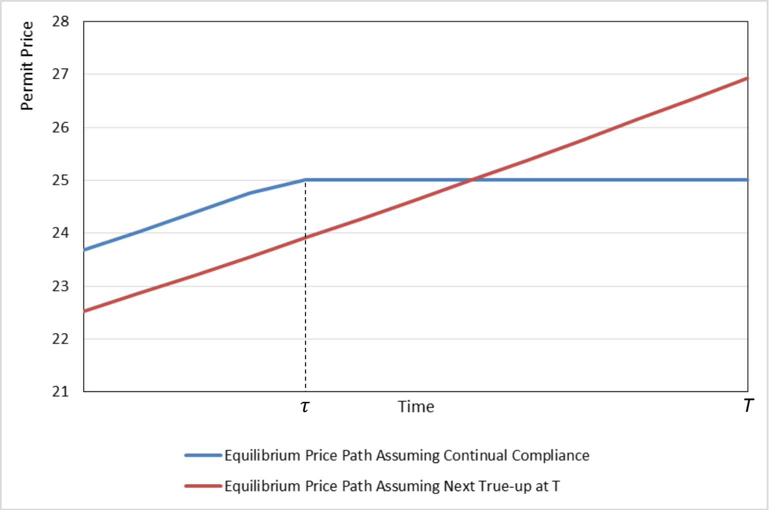
[18] Every cap-and-trade program for carbon implemented or planned in the U.S. includes a reserve price on permit auctions. On the other hand, the emissions trading system of the European Union (EU-ETS) does not use such reserve prices despite the widespread recognition that the current price of permits in Europe is dangerously low. Europe does use reserve prices when auctioning other goods and services. Whatever the political economy explanation is for the differential treatment of pollution permits, in the absence of reserve prices additional permits offered in scheduled auctions are added to the private holdings and further depress already low prices.

Figure 2: The Equilibrium Price Path under Continual Compliance versus under Delayed Compliance in the Absence of Borrowing



I). She predicted that, although no permits would be banked after τ, firms would cover their emissions by surrendering permits as they were acquired.

However, as Schennach herself noted, EPA required true-ups to occur periodically rather than continually so firms could have uncovered emissions between true-ups. If the next true-up occurred at T, no price-taking firm facing the path depicted would behave as she envisioned. Each firm would instead have had an incentive to sell immediately every permit as the government provided it, put the money in an interest-earning account, and buy the same number of permits back at the lower discounted cost when true-up was next required (T). This, of course, would not constitute an equilibrium since there would be no one willing to *buy* the permits offered for sale. Given that the next true-up occurs at T, the equilibrium price path must rise until T at the rate of interest. We depict the actual equilibrium price path if the next true-up occurs at T in Figure 2.

While Schennach mainly focused on a model in continuous time, most stochastic simulation models are formulated in discrete time with each period assumed to have the length of one compliance period. Each period begins after true-up and continues until just after the next true-up. Such models can say nothing about interesting phenomena that have actually occurred within compliance periods: auctions, auctions where nothing sells, speculative attacks where the entire government reserve to enforce a price ceiling sells in a single day, etc.

Rather than have one set of models that only investigates what happens within compliance periods and another set of models that only investigates what happens between compliance periods, it would be useful in the future to have models that encompass both phases.[19] The Holland and Moore (2012) analysis of the price paths of permits induced by the RECLAIM program to control NO_x emissions is an outstanding example working in this direction (see, in particular, their Figure 2).

4.3 Demand Uncertainty versus Regulatory Risk

Most analyses of uncertainty in markets for pollution permits assume that shocks shift the demand for permits up or down in each period. However, there is an additional type of uncertainty in such markets: regulatory risk. In some markets, holders of permits face an ongoing risk that their bank may at an unknown time suddenly become worthless because of an unanticipated end of the program. In other markets, holders of permits face an ongoing risk that their bank will suddenly become more expensive because of a decision announced at an unknown time to tighten the cap.[20] Regulatory risk has had a profound effect in natural resource markets (Salant and Henderson, 1978) and in foreign exchange markets, where pegged exchange rates may suddenly be abandoned (the so-called "peso problem").[21] Given the continual political interventions in permit markets, it would be surprising if ongoing concern about the announcement of a regulatory action at an unknown time would not affect the prices we observe prior to the realization of the uncertainty.

4.4 Dynamic Optimization versus Dynamic Equilibrium

When the competitive equilibrium maximizes some function that can be pre-specified, an analyst can either (1) solve the equilibrium conditions directly or (2) solve the associated optimization problem and then infer the competitive prices indirectly. For example, Samuelson (1971) uses the indirect approach to solve for the competitive equilibrium by maximizing the representative consumer's utility in his study of interseasonal carryovers of grain under uncertainty.

When government policies distort the competitive equilibrium, however, the assumptions

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[19] The literature on grain storage developed in a similar way. Samuelson's stochastic model of carryovers with harvest uncertainty (Samuelson, 1971) omits the the rich sawtooth price dynamics necessary to induce intraseasonal carryovers between harvests. For that, readers must consult the deterministic model in Samuelson (1957). In a deterministic model, if all the harvests were the same size and each period in a discrete-time formulation was one season in length, then the market price in successive periods would be constant: the entire sawtooth pattern would be hidden from view.

[20] Risk of a sudden price jump in one direction at an unknown time may arise even without government intervention as Roll (1984) shows in his analysis of the effect on orange juice futures of an ongoing risk of a killer frost in Florida.

[21] For the origins of this term and a reference to the first paper in the foreign exchange literature to study it, see Krugman's "Trivial intellectual history blogging," July 15, 2008 (Krugman, 2008).

of the first welfare theorem do not hold and the "indirect approach" may result in a mischaracterization of the competitive equilibrium. As Stokey et al. (p. 542, 1989) observe "In the presence of taxes, externalities, or other distortions, this type of attack fails." We are concerned that the attack may have failed in some of the stochastic simulation models we have reviewed.

To illustrate the issue, consider the following simple, two-period, deterministic example. Suppose cumulative emissions over two periods would be E and a regulator wants them to be reduced to $E - A > 0$ by requiring cumulative abatement A over the two periods. Denote the stationary, strictly increasing, strictly convex cost of abatement in each period as $c(a_t)$ for $t = 1, 2$. The regulator makes available in period 1 $E - A$ permits at the outset and requires that one be surrendered contemporaneously for each unit of emissions. Firms sell their permits on competitive markets for p_1 or "bank them" until period 2, earning interest $r = \beta^{-1} - 1$. A firm could then sell the banked permits for p_2 or could use them to cover period 2 emissions. Each firm abates until the marginal cost of additional abatement just equals the price of buying a permit to comply with the regulation. If permits are banked for the next period, the capital gain must compensate for the foregone interest: $\beta p_2 = p_1$.

Suppose the government, concerned that the second-period price not get too high, stands ready to sell up to $G^{\max}$ additional permits at the ceiling price p^C. Then the following equations characterize the competitive equilibrium:

$$\begin{aligned} p_1 &= c'(a_1) && (1) \\ p_2 &= c'(a_2) && (2) \\ p_1 &= \beta p_2 && (3) \\ a_1 + a_2 &= A - G. && (4) \end{aligned}$$

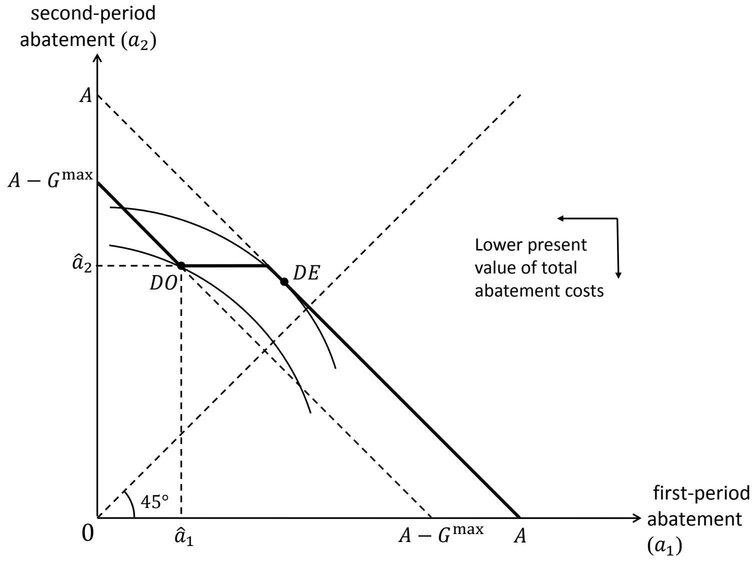
where

$$G \begin{cases} = 0 & \text{if } p_2 < p^C \\ \in [0, G^{\max}] & \text{if } p_2 = p^C \\ = G^{\max} & \text{if } p_2 > p^C \end{cases} \tag{5}$$

Assume the exogenous ceiling price is higher than the equilibrium price ($p_2 < p^C$). Denote by $\hat{a}_2$ the cost-minimizing abatement that would occur if the second-period permit price reached p^C. That is, $c'(\hat{a}_2) = p^C$. The competitive equilibrium occurs at point DE

Since the ceiling does not bind in this competitive equilibrium, $a_2 < \hat{a}_2$. Given our assumption that the $E - A$ permits are available in the first period, there must be banking and so $a_2 > a_1$. Since $p_2 < p^C$, equation (5) implies that in the competitive equilibrium the government would not intervene ($G = 0$) and so the cap would not be relaxed (equation (4) reduces to $a_1 + a_2 = A$). The coordinates of the point DE in Figure 3 indicate the first and second-period abatement in the dynamic competitive equilibrium.

Figure 3: Case where the Indirect Approach Fails to Characterize the Competitive Equilibrium Correctly



The indirect approach would be to minimize

$$c(a_1) + \beta c(a_2) \text{ subject to (4) and (5).}$$

The solution to this dynamic optimization problem occurs at $(\hat{a}_1, \hat{a}_2)$, the coordinates of point DO in Figure 3. By abating little in the first period, the planner puts himself in the position of being unable to satisfy the aggregate abatement constraint without incurring marginal abatement costs in the second period higher than p^C since $c'(A - \hat{a}_1) > p^C$. In doing so, the planner counts on the government to sell up to $G^{\max}$ more permits at the price $p^C = c'(\hat{a}_2)$. The relaxation of the cap means that the planner is no longer required to abate A units of emissions and can save on second-period abatement costs. Such a strategy requires the planner to abandon the intertemporal smoothing. Since point DO is *northwest* of point DE it has both a higher a_2 and a lower a_1 than at point DE. Accordingly, $\beta c'(\hat{a}_2) > c'(\hat{a}_1)$, which can never occur in a competitive equilibrium with permit banking. But the benefit of a relaxed cap more than compensates for the inefficient abatement profile necessary to achieve it. As illustrated in Figure 3, the planner achieves a lower discounted cost than occurs in the competitive equilibrium (point DO is strictly preferred to DE as it lies on a higher indifference curve).

In this example the indirect approach leads to a mischaracterization of the competitive equilibrium.[22] To avoid such a possibility, the safest approach is to solve for the competitive equilibrium directly. For early examples of the procedure to be followed, see the simulations of Gardner (1979) and the analysis of Salant (1983); for a recent simulation based on the direct approach, see Fell (2015).

5 Conclusion

The literature on the dynamics of pollution permits has been developing while actual experience with the new markets for bankable pollution permits has been accumulating. Contributors to this literature have, therefore, faced the daunting challenge of either devising models too abstract to apply to any specific program or too specific to apply to more than one program. To add to the difficulties, many of the arcane provisions of these cap-and-trade programs are being drafted by lawyers seemingly unversed in economic theory. Nonetheless the experience with such programs has been valuable in shaping economic analyses.

We have attempted to identify the principal contributions to this literature and to point to unexploited parallels with the previous literature on commodity agreements and price bands. Permit markets, however, trade an artificial commodity. If the models we have surveyed are any indication, economists did not anticipate that policy makers would insist on maintaining their freedom to change program rules in ways that profoundly affect the value of the permits held by market participants. Their freedom to change the rules at any time subjects asset holders to continual regulatory risk.

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[22] The indirect approach does not always result in error. For example, if the point with coordinates $(\hat{a}_1, \hat{a}_2)$ had strictly higher costs than DE then the direct and indirect approaches would happen to give the same answer (that is, DO and DE would coincide).

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