Derivative Markets for Pollution Permits and Incentives to Innovate

Linda R. Cohen[1] and Amihai Glazer[2]

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Abstract

Innovation can be encouraged by grants of a patent monopoly, subsidies to innovative activities, and prizes to innovators. This paper examines a fourth mechanism---a firm engaged in R&D has private information about whether it succeeded or failed to innovate. It can profit from this private information by buying or selling an asset whose price will depend on whether the innovation is introduced or not. In particular, we look at an innovation which reduces the cost of abating pollution, reduces the prices of pollution permits, and allows the firm engaged in R&D to profit by buying and selling futures for such permits. We determine the government policy which can generate an equilibrium with sufficient profits to induce a firm to invest in R&D, and to induce the firm which made the innovation to charge a zero price for use of its innovation.

1. Introduction

A central issue in climate policy is how to promote innovation that reduces the costs of abatement, or reduces the level of emissions for a given level of production. This paper considers how financial markets that form around pollution trading markets can induce such innovation. We are interested in whether futures markets can reward inventors who trade on their private information about an innovation that will affect the spot price of permits in the

[1] Dept. of Economics and School of Law, U.C. Irvine. contact: lrcohen@uci.edu.
[2] Dept. of Economics, U.C. Irvine. contact: aglazer@uci.edu. We are immensely grateful to Jinwon Kim for superb research assistance and to the UC Center for Energy and Environmental Economics for financial support. Earlier versions of this paper were presented at the UCE3 Conference, June 2010 and the Symposium in Honor of Thomas Schelling at the Sustainability Consumption Institute at the University of Manchester, November 2010. We thank the participants for insightful and useful comments.

future.[3] This analysis follows Hirshleifer (1971). He recounts the story of Eli Whitney, who was unable to enforce his cotton gin patents and failed to profit commercially from the invention. Hirshleifer observes that "what seems to have been overlooked is that there were other routes to profit for Whitney. The cotton gin had obvious speculative implications for the price of cotton, the value of slaves and of cotton-bearing land, the business prospects of firms engaged in cotton ware-housing and shipping, the site values of key points in the transport network that sprang up ..." (p. 571) These pecuniary effects of invention, Hirshleifer suggests, can substitute for patents in giving incentives to innovate. Rather than directly profiting from sales of the invention, the inventor can buy futures for complementary assets (taking a long position in the market) or sell futures for substitutes (taking a short position). An example where speculation in assets generated profits appears with the development of trolley lines. Railroad entrepreneurs in southern California in the early 1900s made their profits not from revenue from the trolley lines they built, but from buying land along the route of the trolley before the line was built, and then selling that land at high prices after the line was built (Sheehan 1982).

Hirshleifer's suggestion has been neglected by students of innovation. This route to innovation appears limited by both practical and theoretical considerations. Among the practical constraints can be the absence of well-developed futures markets for relevant products. A cap-and-trade regulatory regime addresses this problem. Because emission permits are perfect substitutes for abatement technology, futures markets for permits provide an excellent vehicle for speculating on the success of an emissions-related research and development program.

A second practical problem is the substantial wealth endowment or access to capital that research and development (R&D) firms need to speculate. This is a serious objection, as R&D firms experience liquidity constraints in financing their research activities, even without any

[3] The traditional role of futures markets in handling risk can also promote innovation. See Arrow (1964).

additional capital needed for speculation. We suggest that the problem should not derail an investigation of how financial markets affect innovation; rather, should that effect be deemed important, policies to overcome liquidity constraints might deserve more attention. The existence of a permit trading market may be part of the solution, as a wide range of firms and financial institutions can participate in such markets and could collaborate with research-performing firms to take advantage of speculative opportunities.

Chief among the theoretical objections to relying on speculation for incentives to innovate is that a firm with inside information which trades in futures will change the prices of futures contracts and so reveal its private information. We develop a model which in some circumstances solves the difficulty. Our approach relates to that used by Lucas (1972) in discussing how monetary policy can be effective when economic agents are unsure if increased activity is caused by increased money supply or by positive real shocks. Grossman (1977) explores the information-generating incentives of futures markets, deriving a set of conditions under which informed traders can profit from private information on futures exchanges. Like Lucas (1972), his equilibrium provides for the costly production of information only when there exists additional uncertainty whose resolution will affect prices, but is at most weakly correlated to the content of the private information.

Our model adapts these principles to innovation, using the tools of game theory. We consider an economy with no intellectual property rights and with a single speculator (the R&D firm), which trades on private information. The R&D firm knows its trade affects prices, and makes financial transactions to suit. Its strategy is known to other investors (the polluters, who constitute hedgers in this interpretation), but the R&D firm can still keep information private if there exists sufficient uncertainty apart from the research project about the ultimate spot price of permits. We show that under circumstances with economic significance – specifically, for cases where the standard suite of innovation policies is problematic – futures markets can provide incentives to innovate.

A concern with speculation is that the R&D firm may be subject to moral hazard. Consider a speculator who, based on his private knowledge about the lack of innovation, buys futures contracts. He profits because the spot price will be higher than a futures price which incorporates the positive expectation (of everyone else) for innovation. The problem is that the same profits arise when the project succeeds but is not commercialized. Suppose the R&D firm can keep its information private not only in the futures market trading period but can additionally withhold the technology in the spot market trading period, so as to cash in on a long position. This may be more profitable than taking a short position and profiting from innovation.

We analyze the opportunity to support R&D through futures trading markets both when it is possible to withhold an invention and when it is not. Conditions exist in both cases for a perfect Bayesian equilibrium, depending on the cost of the R&D program, its probability of success, and the probability distribution over the state of nature, which in our model constitutes the additional, uncorrelated uncertainty. While rules that restrict an R&D firm from moral hazard appear attractive, we show that they reduce incentives to conduct R&D and, in some important cases, result in less innovation.

The paper proceeds as follows. The next section relates our analysis to recent work on innovation and climate policy. The discussion concludes that the speculative approach could complement other innovation policies. Section 3 presents the basic model and derives conditions for existence of an equilibrium when R&D firms can speculate at will, but may or may not be able to keep a successful project from the market. Section 4 compares the different outcomes. The final section of the paper presents conclusions and discusses potential policy implications.

Section 2. Innovation in Emissions Technology

While claims for superior efficiency of market-based policies to regulate pollution have primarily been grounded in static analyses, the market approaches are also seen as attractive for innovation, by giving rise to demand induced innovation: an incentive for emitters to install emissions reduction technology, and hence for innovators to invent and produce cheaper and more effective ways to reduce emissions. (Newell, Jaffe and Stavins, 1999; Jaffe, Newell and Stavins, 2003). In theory any form of regulation, including command and control strategies, would produce demand for emissions abatement technology. The market approach, however, is thought to have advantages over a command-and-control approach in allowing flexibility in responses and consequently expanding the scope for creativity and successful innovation. (e.g., Downing and White, 1986).

Some empirical support exists for the market preference, although disentangling the contributions of energy price changes, regulatory changes, and lags in technology presents a challenge. (Popp, 2002; Taylor, Rubin and Hounshell, 2005; Lange and Bellas, 2005). Given the youth of most emissions markets, and the plethora of strategies to reduce emissions that do not involve inventions but simply await a more constrained emissions regime (Parry, Pizer and Fischer, 2003), the lack of compelling evidence for large changes in incentives to invest in R&D is unsurprising.

While some regulations that place a price or restriction on emissions are considered to be the biggest single contribution to inducing innovation in emissions technology, the literature on innovation teaches that even textbook competition is inadequate. (Jaffe, Newell and Stavins, 2005; Fischer and Newell, 2008). Because R&D is costly, R&D firms need greater revenues than can be generated by sales priced at marginal production cost of the new equipment. In the United States, recovery of R&D expenses is typically accomplished through a combination of monopoly pricing and public subsidies. Monopoly is supported when patents, trade secrets, or a first-mover advantage lower competition, even if only for a limited time. Public subsidies take a wide variety of forms, including direct support for research, tax credits or deductions, and promises of public procurement at supra-competitive prices or prize money should the R&D project succeed.[4]

The literature on innovation and climate change focuses on how market failures associated with R&D frustrate relying on standard policies – intellectual property rights or the monopoly supply of the new technology – to reward innovators. Carbon markets present particular challenges for innovation. Governments have strong incentives to inflate permit quantities and lower permit prices, due to economic pressures, political business cycles, or even the existence of the new, improved, technology (Montgomery and Smith, 2007). In addition, the international scope of the carbon problem may weaken intellectual property rights (Reichman et al., 2008).

Public R&D – including government directed spending programs, prizes, and collaborations – can fill the gaps left by private activities. As political enthusiasm for carbon constraints of any type has waned in the United States, more attention has been devoted to the problem of how best to organize a public R&D program for climate technology (Newell and Wilson, 2005; Kopp and Pizer, 2007; Hayward et al., 2010). But the litany of problems with

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[4] For a recent analysis of how the standard innovation policies of monopoly and public support can be optimally combined, see Weyl and Tirole (2010).

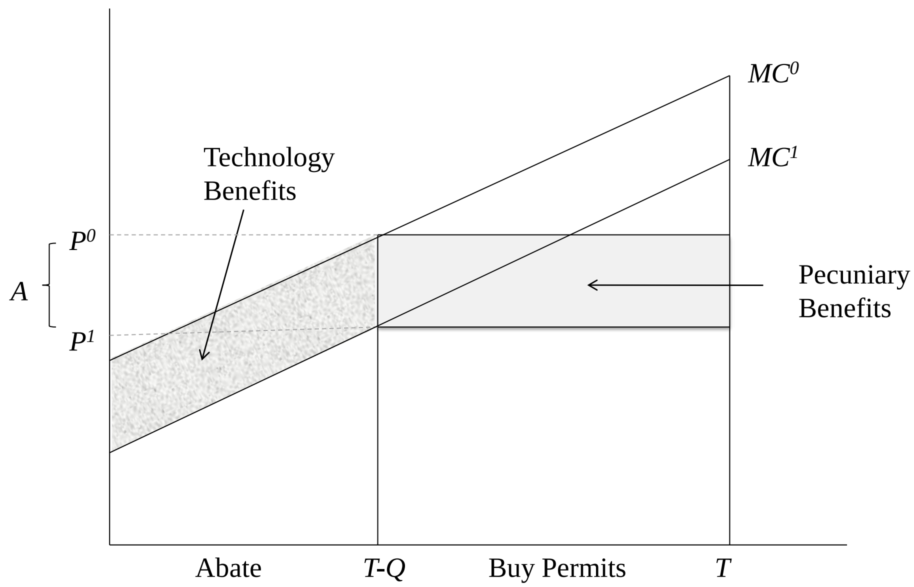
government programs is long (Cohen and Noll, 1991, Sarewitz and Cohen, 2009). The issues with particular relevance for climate technology relate to the high risk for R&D that could produce dramatic cost reductions. The risk implies, first, that substantial agency problems arise for programs that attempt to directly support research: the high uncertainty exacerbates monitoring costs and confounds efforts to properly reward effort. Moreover, the high risks require high pay-offs, increasing costs for policies that attempt to reward successful projects through procurement or prizes. All of these policies have a potential role in climate policy, but experience with other government programs suggests that they may be inadequate to generate the innovations either anticipated or needed for a successful climate policy. This in turn suggests a role for speculation-induced innovation, which, as we show, may be effective at inducing innovation when other policies are not.

Futures markets for carbon permits have been the subject of increased interest in environmental policy scholarship. Ismer and Neuhoff (2009) develop a proposal that uses an options market to solidify the political commitment to a cap-and-trade program and to maintain prices at a previously agreed-to level. Much technology for abating emissions requires investments which have a long-term payoff of reducing fossil energy use. Futures and other financial instruments allow emitters to reduce the risks of long-term investments (Helm and Hepburn, 2007) and to manage price volatility in the energy area (Pirog, 2006). As a result, they should contribute to demand for new technologies embodied in long-term investments, and increase the extent of demand-induced innovation.

Our analysis investigates a different effect of futures markets: they may directly provide R&D firms with profits when the firms introduce new technology. The mechanism works separately from intellectual property; indeed, as we shall see, associated profits can be highest in the absence of intellectual property. Thus, the mechanism is of considerable interest for climate regulatory regimes characterized by poor intellectual property regimes.

We first consider a world where the only factor that might influence the price of emissions permits is a technological innovation. As we shall see below, the outcome is not sustainable, but it serves to illustrate how the proposal addresses some of the deficiencies in the current policies. The simple model is illustrated in Figure 1. Abatement is measured along the horizontal axis, and the marginal cost of abatement on the vertical axis. Total potential emissions, or emissions in the absence of any abatement, are indicated by T. The regulator has determined that a fixed number Q of permits will be available, so that T-Q emissions are abated and Q units are emitted. Initially the marginal cost of abatement is given by the curve MC^0. The equilibrium price of a permit is P^0. The total cost to industry is the sum of abatement costs, or the area under the marginal abatement cost curve between 0 and $(T\text{-}Q)$, plus P^0Q, the total cost of the permits.

FIGURE 1: Profiting from trading in futures contracts



Suppose a major new technology reduces marginal costs for all sources of pollution, shifting it down by the amount *A*. Under cap-and-trade regulation, emissions and abatement remain identical, but the cost of abatement and the price of permits decline. All abaters install the new technology. The price of permits falls to $P^1 = (P^0 - A)$, and in aggregate, polluters save *QA* on their permit costs. For simplicity, suppose that the new technology, or equipment, can be produced at zero marginal cost. Then the social value of the technology, or what Hirshleifer called the technology benefits, is the area between the two abatement curves for the abaters, shown in Figure 1, less development costs. The decline in permit price has no social import, but constitutes the pecuniary value of the innovation.

The R&D firm – knowing that once its technology is introduced the price of permits will fall – sells a future at the ex ante market price, P^0. That is, it gets P^0 now. At a future date, when it must deliver the permits, the R&D firm buys permits at the market price P^1, making a profit of

A per permit. Of course, this does not necessarily result in a profit at all commensurate with the social value of the invention. The pecuniary benefits may far exceed the social benefits, or be much less; the return to the R&D firm depends in addition on the price specified by the futures contract. We discuss these issues further below and in section 4, for now assuming that an R&D firm can realize a return that compensates it for its risks and R&D outlays.

This Hirshleiferian effect, like the patent system, rewards success, and thus creates an incentive for R&D firms to work hard. Unlike the patent system, it generates incentives to innovate with no governmental evaluation of the innovation for patent-worthiness, and no litigation about patent rights. Unlike the patent system, the mechanism creates an incentive for broad diffusion of the technology. The R&D firm's goal turns from maximizing profits on sales to minimizing the permit price at a future date. The incentives are structured for the invention to be literally given away. Thus, the system, if it works, is in theory more efficient than a patent system with its necessary static inefficiency.

Turning to innovation policy for climate technologies, we see that the proposal addresses one important problem: the conflict between government and R&D firms over intellectual property. In this example, both parties pursue low prices. Alternatively, the policy requires that the government uphold the futures contracts. Recent history with politically unpopular speculative contracts in real estate in the United States suggests that such contracts will be honored, even when the rewards appear unjustified.

As sketched out here, once the R&D firm starts speculating in the futures market the price falls and its information becomes public. As a result, the price of futures should fall to the ultimate spot price, P^1, so no profits accrue to speculation.

Before addressing this issue, we note that there exist financial markets for pollution permits. Our interest is in futures markets, where buyers and sellers are anonymous to each other, allowing the possibility that an R&D firm could trade without revealing it is doing so. A futures contract is a standardized agreement in which the seller (called the short) contracts to deliver a specified quantity of emissions permits at a fixed time in the future, at a price agreed to when the contract is first entered into. The other side of the contract is the buyer, called the long. Before expiration of the contract, the buyer's and seller's counterpart is the clearing house, which provides a financial guarantee of performance. A futures contract thus differs from a forward contract; a forward contract is made between a buyer and a seller who know each other's identity, and so such a market lacks anonymity. For example, the Chicago Climate Futures Exchange introduced futures markets for SO_2 permits in 2004, with active trading beginning in March 2005. Futures trading on the Chicago Exchange was nearly 1.9 million allowances in the first half of 2007. In April, 2007, the Chicago Exchange began offering options on permits (Jickling and Parker, 2008).

Europe, which has adopted a cap-and-trade system for limiting carbon emissions, has a well-developed futures market, ECX, for permits.[5] Over one hundred firms, including Barclays, Goldman Sachs, and Morgan Stanley have signed up for membership to trade ECX products. In the two years following the founding of the futures market in 2005, it has traded more than 989 million tons in futures contracts. So markets exist in which the trades we have in mind can occur, and sophisticated firms engage in those markets. Their participation suggests a potential funding mechanism for R&D firms that plan to deploy the strategy discussed here to profit from R&D investments. Financial firms routinely take equity positions with R&D firms and share in

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[5] See e.g., European Climate Exchange trades 1 bln tons CO2 | Reuters, at http://www.reuters.com/article/2007/07/11/environment-markets-carbon downloaded 3/16/2011.

profits; here the arrangement would involve sharing information so as to profit from insider trades.[6]

We are not aware of any empirical studies that consider whether futures markets affect innovation by allowing R&D firms to speculate on private information. However, the potential for financial instruments to play such a role is supported by the study of Coff and Lee (2003). They find abnormal returns to stocks in R&D intensive companies following announcements of insider trades. The study is consistent with the possibility of trading on private information (although here it is stocks in companies, rather than commodity futures), and with R&D activities generating private information for insiders. Further evidence that not all information is instantly public, or that profits can be made from private information, is given by Cohen, Malloy, and Pomorski (2010), who find that insiders within a firm profit from their private information by trading in the stock market.

Section 3. Futures Markets and Innovation

We now turn to the existence of an equilibrium with innovation where profits flow from pecuniary benefits. Consider a cap-and-trade regime for greenhouse gases with trading in both spot markets and futures markets. Permits are traded on exchanges. Permit prices will reflect both abatement costs and demand for final products, and firms can trade anonymously. We restrict attention to the case where there are many emitters (or emitting firms) and a single R&D firm that, if successful, produces an innovation that reduces the cost of abatement to zero.[7] While it cannot appropriate the returns to its invention – the cost of permits following the

[6] Clearly, one of the policy issues that would need elaboration is the legality of such arrangements. This is beyond the scope of this paper.

[7] In the models in this paper we rule out participation in the futures markets by other financial firms. Of course such firms do participate in the pollution permit derivative markets. Generalizing the model to allow for speculators in addition to the R&D firm is an important topic for further research.

introduction of the invention falls to zero – it will, for some time, have private information about whether the R&D program is successful and thus be able to speculate on the futures market. The R&D firm is risk neutral, but the emitters are risk averse.

Critical to the R&D firm's ability to profit in this set-up is that additional noise obscures the signal it would otherwise transmit through its own actions in the futures market. In the greenhouse gas context, the requirement is naturally met by demand shocks for final goods whose production requires energy. We assume that in the final period of the game, were there no greenhouse gas controls, emissions would be either high or low (*H* or *L*), depending on the realization of demand. Furthermore, we assume that there is sufficient variation in demand shocks that no emitter can infer aggregate demand from its individual schedule. This set-up plausibly relates to the greenhouse gas regime as emissions come from a very broad array of industries and activities.

We posit a regulatory regime with a fixed number of permits *Q*. The emitting firms in the aggregate need to abate an addition $(H - Q)$ units of pollution when demand is high and $(Q - L)$ units of pollution less when demand is low relative to that anticipated when the government chose the emission cap. Excess demand or excess supply changes the permit prices in the spot market to equal the marginal abatement costs in each of the two regimes.[8] Absent the R&D firm, the true state of the world would be revealed through trading in the futures market: while each firm knows only its demand, the market clearing prices in the futures market and spot market would be p_H or p_L.

The time line follows:

[8] More precisely, there exists a positive number *Z* such that, absent any abatement, pollution would be $H + Z$ and $L+Z$ in the two states of the world, so that the number of permits *Q* always leaves some residual pollution. For notational simplicity we suppress the term *Z* .

1. In period 1, the government chooses a permit level *Q* and distributes the permits to the emitters.

2. In period 2, the R&D firm can invest a fixed cost, *F*, in R&D. We denote a successful outcome for the R&D program by *I*, which occurs with probability *s*, and an unsuccessful outcome by $\tilde{}I$.

3. In period 3, Nature determines demand for the final goods. At this time the true state of the world is one of four states denoted by the set $T \in \{(H, I), (H, \sim I), (L, I), (L, \sim I)\}$. The notation *(H, I),* for example, means that demand for abatement is high and the R&D firm discovered a cost-reducing technology, and similarly for the other pairs.

4. In period 4, all firms, including the R&D firm, can buy and sell futures. Common knowledge is the probability *h* that demand for permits is high. The R&D firm has private information on whether the R&D project is a success; other market participants know the prior probability of success, *s*. In the course of trading the market will signal net demand for permits *X*, which equals demand for permits in the two states of the world (*H* or *L*) as modified by the actions of the R&D firm: adjusted down should it sell futures contracts, or up if it takes a net long position and buys contracts.

5. In period 5, conditional on *I* occurring, the R&D firm can choose whether to introduce the innovation or not. If the innovation is introduced, the spot price for permits in period 5 will be zero. If no innovation is introduced, the spot prices are p_L or p_H. Future trades are settled, and firms can buy and sell permits on the spot market.

Consider first the case where the R&D firm cannot suppress the invention from commercialization in period 5. If *I* occurs, then the spot price in period 5, in both *H* and *L* states, falls to zero. We establish the equilibrium in two parts. First, we show that an equilibrium can exist that generates positive revenues for the R&D firm, assuming that it has undertaken the R&D project. We then consider whether the mechanism provides sufficient incentives to justify investment in R&D.

Proposition 1. Let h $(0 < h < 1)$ be the probability that the demand is high and let s $(0 < s < 1)$ be the probability that the research program succeeds. Suppose the R&D firm invests in the R&D project in period 2. If the project succeeds, the technology will be available. Then there exists a perfect Bayesian equilibrium composed of a regulatory cap on pollution of Q permits which government distributes to emitters in period 1, and a pair of positive futures prices p_H and p_E such that futures permits trade at p_H in state *(H, ~I)*, at p_E in states *(H, I)* and *(L, ~I)* and at 0 in *(L, I)* where:

$$(1) \qquad p_E = \frac{(1-h)(1-s)p_L}{hs + (1-h)(1-s)} = \alpha\, p_L$$

and

$$(2) \qquad Q = (1-\alpha)H + \alpha L p_L$$

At this equilibrium, the R&D firm obtains expected positive revenues. (The proof is contained in the appendix.)

The intuition for the result is as follows. The aggregate amount of permits held by emitters is Q, but in both states H and L, some emitters will have more permits than they will need and others fewer. If futures contracts trade at the expected spot price, all of the emitters will enter the market to precisely cover their demand, as, being risk averse, they prefer a futures contract at the expected spot price to buying or selling on the spot market. If the state of nature is H, trade among themselves would reveal excess demand for permits of $(H – Q)$ and if the state of nature is *L*, their trades would reveal excess supply of *(L - Q)*. Were there no R&D, the futures price would equal the spot price of either p_H or p_L, respectively.

However, the R&D firm may participate in the market. The emitters maintain the following beliefs in equilibrium:

(i) If they observe excess demand *H – Q*, then they believe that the state of the world is *(H, ~I)* and the R&D firm is not participating in the market. The futures price will be p_H.

(ii) If they observe excess supply *Q – L* then they believe that the state of the world is *(L, I)* and the futures price will be 0.

(iii) When they observe no excess supply or demand, then emitters believe that the R&D firm is participating in one of two ways: first, the state of the world is *(H, I)* and the R&D firm has sold *(H – Q)* contracts; and second, the state of the world is *(L, ~I)* and the R&D firm has bought *(Q – L)* contracts. These actions by the R&D firm result in no excess demand or supply in either of the two states, so they are indistinguishable to the emitters. The futures price p_E, given in (1), is the expected period 5 spot price, given these beliefs.

The futures prices in (i), (ii) and (iii) equal the expected spot price conditional on the beliefs of the emitters. Thus, the emitters are content to participate in the market at all three prices.

To establish the existence of the equilibrium, we need to show that the R&D firm will sell and buy futures as expected by the emitters. At *(H, ~I)* the result is immediate: when the R&D project failed, the R&D firm can make money on the futures market only if the price on the futures market is lower than the spot price. At p_H the futures price equals the spot price so no profit is available. Similarly, at *(L, I)* the futures price is zero and there is no incentive for the R&D firm to participate in the futures market. We note that there is also no incentive in this model for the R&D firm to commercialize the technology at *(L, I)*, but we assume that someone will do so anyway. The next section allows for the R&D firm to limit commercialization in this case.

Here, the equilibrium price p_E leads the R&D firm to take action consistent with the expectations of the emitters. Because p_E is positive, the R&D firm will want to sell at *(H, I)*. Furthermore, p_E is less than p_L so the R&D firm will profit from buying futures in *(L, ~I)*. If the R&D firm sells precisely *(H-Q)* or buys *(Q – L)* contracts, then these amounts must maximize the profits that the firm can make from buying and selling, and thus depend on off-equilibrium beliefs of the emitters. The appendix shows that a rational set of beliefs exists that satisfy the maximum condition simultaneously for *(H, I)* and *(L, ~I)* as long as *Q* is defined by the expression in equation (2). Given regularity conditions on beliefs and actions, this equilibrium is unique for each value of *s* and *h*.[9]

While there are positive revenues associated with each equilibrium identified in Proposition 1, the R&D firm should only undertake a project if it expects to make money from commercializing it. This imposes an additional condition on the existence of an equilibrium:

Proposition 2: (Participation Constraint) For *(h, s)* and the associated permit cap *Q* defined in equation (2), the R&D firm expects to generate sufficient revenues from trading in the futures market to justify undertaking the R&D project if:

$$(3) \qquad sh(H-L)\alpha^2 p_L > F$$

where *F* is the cost of the R&D project.

Expected profits for this equilibrium are:

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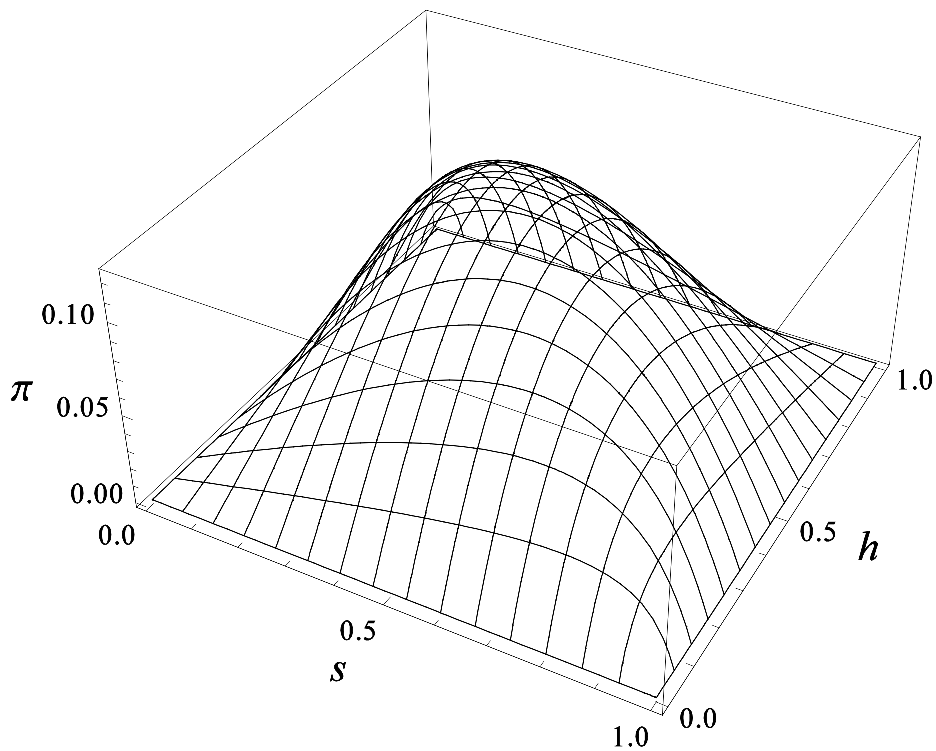
[9] A sufficient condition is that the beliefs result in an off-equilibrium monotonic, differentiable relationship between the observed demand and the futures price, and that the R&D firm pools at a single apparent level of demand. The second condition is equivalent to an efficiency constraint. Precise conditions are contained in the appendix.

$$(4) \qquad \pi(s,h) = \frac{sh(1-h)(1-s)}{hs+(1-h)(1-s)}\ p_L\,(H-L)\ -F = sh\alpha p_L(H-L) - F$$

The profit function is plotted in Figure 2.[10]

FIGURE 2: Profits of the R&D firm



Expected profits are maximized when *s* and *h* are both ½, while the left-hand side of equation (3) obtains a maximum when *s* and *h* are both approximately 0.4. Turning first to expected profits, note that uncertainty works to the advantage of the R&D firm: its inside information is least predictable by emitters, and it can hide the information most effectively when both sources of uncertainty are largest. Alternatively, the participation constraint, which depends only on revenues when the R&D firm profits from the invention, is least binding when

[10] Figure 2 plots profits when $p_L = 1$, $(H-L) = 1$, and $F = 0$. Clearly, expected profits increase with the spot price of permits for low demand and for a greater range of uncertainty, $H-L$.

the project is somewhat riskier. This allows an equilibrium at a level that supports the R&D firm selling additional futures contracts.

The pecuniary profits that the R&D firm can obtain are considerably less than the amount posited by Hirshleifer. While the R&D firm here profits from both success and failure, the extent of its trading is not dictated by the total savings to permit holders from an innovation, but rather by the extent of uncertainty over demand so that the firm can maintain its inside information.

Section 4. A Moral Hazard Equilibrium and other Extensions

This section analyzes how incentives to innovate vary with the constraints facing the R&D firm. We distinguish here between invention – a successful outcome to the R&D project – and innovation: the development and sale of the technology. A futures market may give an incentive to the R&D firm to invent but not innovate. In particular, if emitters believe that an innovation may be introduced in period 5, then the futures price can be lower than the spot price and the R&D firm may be able profit more from taking a long position and not innovating than from commercializing its invention. We first consider whether we can limit the extent to which the R&D firm profits from a failure to innovate. This turns out to be an exercise in futility. Any equilibrium entails at least some conditions under which the R&D firm buys futures contracts. The other extreme also cannot hold: the futures market will not entice the R&D firm always to withhold its invention and refrain from short sales.

Proposition 3. The only perfect Bayesian equilibria that provide an incentive to invest in R&D from financial markets require that the R&D firm buys futures in some states of the world and sells futures in other states. This holds whether or not the firm can withhold its invention.

An equilibrium where the R&D firm only buys futures effectively violates the condition that its information remains private during the futures trading period. While other firms may not know whether the R&D firm invented, they know that no innovation will occur and therefore the spot price will be either p_H or p_L, which is the same market information held by the R&D firm. (It also necessarily violates rationality as there is no reason for the R&D firm ever to invest in the R&D project in the first place.)

The problem with a short-sales only equilibrium is not that inside information needs to be divulged, as in principle it doesn't: if the R&D firm always sold *(H – L)* futures in *(H, I)*, and otherwise did not participate, then the emitters would be unable to distinguish between *(H, I)*, *(L,I)*, and *(L, ~I)* when the distributed permits $Q = L$ and the futures market signals no excess demand. However, it is not possible to construct a set of off-equilibrium prices that induce the R&D firm to behave in this fashion. Either the price when market demand is close to *L* is so large that the R&D firm will prefer to sell fewer than *(H-L)* permits, or the price is so low that the R&D firm will want to buy futures in *(L, ~I)*.

We next turn to the existence of an equilibrium when the R&D firm can choose when to innovate, conditional on invention.

Proposition 4. Let h $(0 < h < 1)$ be the probability that the demand is high and let s $(0 < s < 1)$ be the probability that the R&D succeeds. Suppose the R&D firm invests in the R&D project in period 2 and can choose in period 4, conditional on the project's success, whether or not to make the innovation available to emitters Then there exists a perfect Bayesian equilibrium composed of a regulatory cap on pollution of *W* permits, which government distributes to emitters in period 1, and a pair of positive futures prices p_H and p_F such that futures permits trade at p_H in state *(H,*

~I) and at p_F in states *(H, I), (L, ~I)* and *(L, I)*. At this equilibrium, the R&D firm obtains expected positive revenues and:

$$(5) \qquad p_F = \frac{(1-h)p_L}{hs + (1-h)} = \gamma p_L > \alpha p_L$$

$$W = (1 - \gamma)H + \gamma L < Q$$

Unlike the case with no moral hazard, expected profits in this equilibrium do not obtain an interior maximum. Instead, expected profits are maximized when *s* is as large as possible and *h* is small. The participation constraint is also maximized when *s* is as large as possible and when *h* is ½. When the R&D firm can squelch its invention, it can maintain inside information as *s* approaches 1 – indeed, in theory, even at 1 – because the emitters will still not observe the invention in the low demand state, and the R&D firm can trade so as to obscure the state of the world. However, it may be unreasonable to assume that the R&D firm can withhold an invention when emitters know that the firm has successfully invented, as is implied by $s = 1$. From this perspective, a more reasonable condition for profit maximization is that *s* is as large as possible, consistent with maintaining the R&D firm's ability to withhold its invention.

A prohibition on squelching the results of the R&D program results in a lower futures price in equilibrium than the unconstrained case, as is consistent with the greater availability of the innovation. Due to both the lower price and the more limited trading opportunities for the R&D firm, the constrained equilibrium also results in lower profits to the R&D firm than were it able to choose whether or not to make the technology available to emitters. To maintain the equilibrium, the permit cap needs to be higher in the no-squelching case than were squelching tolerated. Lastly the lower price and higher cap together imply that the participation constraint is always more stringent when the R&D firm is not allowed (or cannot) withhold its technology than when it can. The implications of the final comparison are developed in the next proposition.

Proposition 5. The range of R&D projects that can be supported by speculating in futures markets is limited to less expensive projects when the R&D firm is unable to choose whether to commercialize the technology than when it can withhold a successful invention. As a result, while more technology is introduced in states of the world where demand is low, less technology is available when demand for permits is high.

Section 5: Discussion

Most innovation policy and economic analyses of innovation assume that market incentives to innovate arise when R&D firms profit from licensing or manufacturing the invented technology. When innovations are not appropriable, policies turn to some subsidy mechanism. In this world, uncertainty is a problem: the asymmetric information and moral hazard generated by uncertainty over the outcome of the R&D endeavor undermine the efficiency of direct subsidy approaches. Uncertainty means successful R&D firms will demand supra-competitive rates of return, limiting the practical use of prize mechanisms to either few cases or cheap cases. Furthermore, when innovation requires large investment, uncertainty by polluters about how much they will have to abate reduces the effectiveness of demand-driven incentives to invest in R&D.

The incentive to innovate explored in this paper makes a virtue of uncertainty. Uncertainty about whether an R&D investment will succeed creates private information; uncertainty about the demand for pollution permits allows the R&D firm to take advantage of its private information.

This work raises several policy issues. First, financial instruments are often viewed skeptically, especially after the financial collapse that led to the Great Recession, and are likely to be subject to heightened regulatory oversight. A typical comment is that of Senator Byron Dorgan objecting to a cap-and-trade program: “I know the Wall Street crowd can’t wait to sink their teeth into a new trillion-dollar trading market in which hedge funds and investment banks would trade and speculate on carbon credits and securities. In no time they'll create derivatives, swaps and more in that new market. In fact, most of the investment banks have already created carbon trading departments. They are ready to go. I'm not.” [11] Our analysis suggests that these markets can promote innovation. Consequently, proposals to regulate and constrain markets for derivatives in pollution permits should consider this possibility.

Second, the analysis turns on a cap-and-trade market for permits. A large literature addresses the effect on innovation of alternative emission control mechanisms, focusing in particular on taxes versus permits. (Recent contributions include Scotchmer, 2010; and Kolstad 2010). Because the permits markets support futures markets, our analysis provides some support for regulating by quantity, although in theory an optimal tax approach could also induce a derivative market that can support incentives to innovate.[12]

Third, our analysis abstracts from liquidity concerns. It is not immediately apparent that it is more difficult for a firm engaged in R&D to acquire financing when profits come from speculating in futures than when profits come from sales of technology. But clearly the problem requires analysis, with possible implications for loan guarantee policies and restrictions.

Fourth, budgets for public subsidies for research, development and demonstration are limited. Economic guidance for prioritizing projects has focused on situations where patents provide inadequate incentives to innovate. While we show that financial markets can provide incentives to innovate in some economically significant situations, the mechanism fails in other

[11] http://www.bismarcktribune.com/news/opinion/mailbag/article_c337fb0c-434a-51a4-ae35-d57bb0357997.html
[12] For example, a tax policy could, in theory, equate the tax rate with marginal abatement costs, and thus, like the permit price, change with technology. The futures market contracts would then turn on expected tax rates.

cases. Thus, our analysis suggests an additional set of considerations for prioritizing public subsidies for climate research.

Our analysis can be seen as providing an existence proof---we described one mechanism that can induce innovation by allowing the firm engaged in R&D to profit from financial transactions. We suspect that other mechanisms can also work, as when polluting firms are risk averse, and financial firms, in addition to the R&D firm and the polluting firms, trade in futures.

The mechanism we describe here provides incentives for only some kinds of innovation. Most critically, the technology needs to substitute for the “marginal” abatement technology that is determining permit prices. But these are among the technologies that are perhaps most problematic for standard innovation policies: they are likely to be risky; they are certainly the most likely to engender political pressure to restrain from monopoly pricing. The Hirshleiferian mechanism may thus provide a valuable addition to our portfolio of innovation policies.

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Appendix

Proof of Proposition 1

To establish the existence of a perfect Bayesian equilibrium we need to find a set of prices, rational beliefs and a permit cap such that (1) the emitters participate in the market in equilibrium; (2) the R&D firm makes positive revenues in equilibrium (conditional on investing in R&D in period 1); (3) in equilibrium the R&D firm's actions are consistent with the beliefs of the emitters; and (4) faced with the on-equilibrium and off-equilibrium beliefs of the emitters the R&D firm will choose to remain on the equilibrium. Conditions (1), (2) and (3) are established in Section 3; here we prove condition (4). We seek a relationship $p(X)$ such that:

(i) $p(Q) = p_E$

(ii) $p(X)$ is an increasing function of $X \in [L, H]$; $p(X) = 0$ *for* $X < L$ *and* $p(X) = p_H$ *for* $X > H$

(iii) $p(X)$ derives from rational beliefs by emitters on observing excess demand of $(Q\text{-}X)$ or excess supply of $(X\text{-}Q)$

(iv) $p(Q)$ maximizes the profits of the R&D firm for all values of X and all states of the world T.

Let:

$$(A1) \qquad \beta = \alpha + \frac{X - Q}{H - L}$$

where Q and α are defined in equations (1) and (2), and:

$$(A2) \qquad \begin{aligned} p(X) &= 0 && \text{if } \beta < 0 \\ p(X) &= \beta p_L && \text{if } 0 \leq \beta \leq 1 \\ p(X) &= p_L && \text{if } \beta > 1 \end{aligned}$$

Profits for the R&D firm are:

(A3) $\pi(X, p(X)|(L, \sim I)) = (p_L - p(X))(X - L)$ when the state of the world is $(L, \sim I)$

(A4) $\pi(X, p(X)|(H,I)) = p(X)(H - X)$ when the state of the world is (H, I).

Substituting for *p(X)* from (A2) and (A3), it is straightforward to show that the profit functions in (A3) and (A4) obtain unique maxima at $X = Q$.

The off-equilibrium beliefs that result in the price relationship *p(X)* is that on observing excess demand of $Q - X$ (or excess supply of $X - Q$), the emitters believe that the state of the world is *(H, I)* with probability β and is in state *(L, ~I)* with probability (1 – β). Then *p(X)* is the expected spot price and the emitters will trade. The R&D firm, alternatively, will never choose to sell contracts in *(H, I)* other than $(H - Q)$, nor buy in state *(L, ~I)* at any quantity other than $(Q - X)$.

The outcome is unique under two assumptions: (1) the beliefs require that the relationship between observed excess demand/supply and the futures price is monotonically increasing and differentiable at *Q*; and (2) the R&D firm chooses to pool at a single point. Under these conditions the only equilibrium requires that the pooling occur at $Q = (1\text{-}\alpha)H + \alpha L,$ and that the futures price is as given in equation (1) . To establish uniqueness for the outcome, note that if *P(X)* exists such that *P(X)* is differentiable, then if a maximum exists for both $\pi(X, p(X)|(L, \sim I))$ and $\pi(X, p(X)|(H, I))$ at some permit cap level *Z*, it must be the case that

(A5) $\partial\pi(.,L)/\partial Y = (p_L - p(X)) + (X\text{-}L)(\text{-}p'(X)) = 0 \text{ at } X = Z$

(A6) $\partial\pi(.,H)/\partial Y = \text{-}p(X) + (H\text{-}X)p'(X) = 0 \text{ at } X = Z$

rearranging (5) and (6), and requiring that at the equilibrium the futures price must equal the expected spot price:

(A7) $p'(Z) = (p_L - p(Z))/(Z\text{-}L) = p_L(1\text{-}\alpha)/(Z\text{-}L)$

(A8) $p'(Z) = p(Z)/(H\text{-}Z) = p_L\alpha/(H - Z)$

solving (7) and (8) for X:

(A9) $Z = H - \alpha(H - L)= Q$

Thus, the only equilibrium that exists requires that the permit cap be set at Q, with the associated spot price p_E .

Proof of Proposition 2.

With substitutions from (1), and (2), expression (3) is the profits to the R&D firm from its trades in *(H, I)* times the probability of *(H,I)* occurring. This amount must exceed the cost of the R&D program to justifying undertaking it.

Proof of Proposition 4.

The proof of Proposition 4 follows the identical logic to that for Proposition 1, substituting γ, p_F and W for α, p_E and Q.

Proof of Proposition 5.

The equilibrium price p_E in the case where the R&D firm cannot withhold a successful invention is lower than p_F, the equilibrium price when it can; while the number of issued permits Q is larger than W. As a result the R&D firm sells fewer contracts in *(H, I)* in the no-withholding case, and at a lower price, than in the unconstrained case. Thus the R&D firm will invest in some R&D projects in the unconstrained case which it does not invest in when it is not allowed to squelch inventions. As inventions are commercialized in *(H, I)*, a wider range of technology will exist in the high demand state of the world under the squelching equilibrium.