UNIVERSITY OF NOTTINGHAM

Discussion Papers in Economics

Discussion Paper
No. 03/20

ENVIRONMENTAL UNCERTAINTY AND IRREVERSIBLE INVESTMENTS IN ABATEMENT TECHNOLOGY

by Bouwe R. Dijkstra and Daan P. van Soest

October 2003 DP 03/20

ISSN 1360-2438

UNIVERSITY OF NOTTINGHAM

Discussion Papers in Economics

Discussion Paper
No. 03/20

ENVIRONMENTAL UNCERTAINTY AND IRREVERSIBLE INVESTMENTS IN ABATEMENT TECHNOLOGY

by Bouwe R. Dijkstra and Daan P. van Soest

Bouwe Dijkstra is Lecturer, School of Economics, University of Nottingham and Daan van Soest is Researcher, Faculty of Economics, Tilburg University

October 2003

Environmental Uncertainty and Irreversible Investments in Abatement Technology*

Bouwe R. Dijkstra

University of Nottingham

Daan P. van Soest

Tilburg University

October 2003

Abstract. We analyze the design of optimal environmental policy when environmental damage is uncertain and investments in abatement technologies are irreversible. We assume that the investment in the new abatement technology can be used for two periods and that the true extent of environmental damage will become known in the second period. The optimum can be implemented with taxation for heterogeneous firms and with tradeable permits combined with banking. Consistent with intuition, we find that an increase in expected damage unambiguously calls for higher environmental taxes (or tradeable emission permit prices) in period 2. However, taxes should be reduced in period 1 if firms are sufficiently homogeneous.

JEL classification: D80, D92, Q20.

Key words: investment, pollution abatement, irreversibility, uncertainty, environmental policy.

Correspondence: Bouwe R. Dijkstra, School of Economics, University of Nottingham, Nottingham NG7 2RD, UK. Tel: +44 115 8467205, Fax: +44 115 9514159, E-mail: bouwe.dijkstra@nottingham.ac.uk

*We thank Matti Liski, Andries Nentjes, Till Requate, Sjak Smulders and Zheng Zhang for valuable comments.

1 Introduction

Environmental policy making is hampered by the fact that actual damage from economic activity is rarely known with certainty. However, with more data becoming available and measurement and assessment techniques improving over time, this uncertainty diminishes as time goes by. The problem we address in this paper is that while better information about the relationship between economic activity and the state of the environment will become available in the future, environmental policies must be implemented today to mitigate damages arising from current economic activity. After government policy has induced firms to install (typically long-lived) abatement capital based on today's best available knowledge about environmental damage, emission targets may have to be revised if new information reveals the polluting substance to be more (or less) damaging than previously believed, rendering the initial rate of investment suboptimally low (high) in hindsight. While underinvestment simply requires installing additional abatement capital, society directly incurs costs in case of overinvestment as most of the investment expenditures are sunk as soon as the technology is installed.

We develop a multi-period model in which abatement capital can be used for two periods but where accurate information about environmental damage only becomes available at the beginning of the second period. We find that policy prescriptions may change drastically when investments are irreversible. One might conjecture that the level of environmental taxes (and, for that matter, the price of tradeable pollution permits) is always increasing in expected damage. This is valid if uncertainty persists throughout the planning period or if all decisions can be reversed at zero cost. However, if environmental uncertainty is resolved in the second period, the optimal first-period environmental tax may actually be decreasing in expected environmental damage. This surprising result holds if firms are sufficiently homogeneous in terms of their sunk investment costs.

We only consider irreversibility in abatement investment, not in environmental damage.[1] The literature has found that if damage is irreversible, environmental policy may

[1] See Dixit and Pindyck (1994) for a general analysis of irreversibility.

have to become stricter (Arrow and Fisher, 1974; Henry, 1974; Hanemann,1989; Heal and Kriström, 2002); if abatement investments are irreversible, environmental policy should be more lenient (Jou, 2001).[2] When there are irreversibilities both in environmental damage and in abatement (Kolstad, 1996ab; Pindyck, 2000; Saphores and Carr, 2000), environmental policy should become stricter or more lenient, depending on which irreversibility is more important. In a simulation of the greenhouse effect, Kolstad (1996b) finds that the irreversibility in damage is irrelevant, suggesting we should only worry about irreversibility in abatement investment.

Our result that higher expected environmental damage does not necessarily call for higher current environmental tax levels is obtained from an analysis of the firm's decision making process. As the (improved) abatement technology can be used for two periods, a higher future environmental tax level increases the profitability of adopting an improved abatement technology, and hence may result in overinvestment in the current period. As investment costs are irreversible, the government can prevent wasteful investment by reducing the current environmental tax level. Therefore, our model is a technology adoption model similar to those by Kennedy (1999), Kennedy and Laplante (1999), Gersbach and Glazer (1999) and Requate and Unold (2001, 2003).[3] Unlike Requate (1995, 1998), Petrakis (1999) and Jou (2001) we ignore the output market. In contrast to the previous literature, we do take into account that there are both fixed and variable costs associated with abatement. We introduce additional realism in that we consider the possibility of firm-specific set-up costs. We assume a continuum of firms, so that each firm is incapable of influencing environmental policy.

Dosi and Moretto (1997) and Kennedy (1999) have previously incorporated irreversibility into a technology adoption model. Dosi and Moretto's (1997) setup differs from ours in two important respects: in their model, the uncertainty pertains to the firm's private benefits of adopting the clean technology, and the government's goal is for the industry to switch to a clean technology at a certain point in time rather than

[2] Viscusi (1988) extends the analysis to the case where the investment level can be adjusted downward or upward with adjustment cost. With upward adjustment cost, it may be optimal to start with a large investment.

[3] Jaffe et al. (2002) review the broader field of environmental innovation.

social welfare maximization under uncertainty. The information structure in our model is similar to Kennedy's (1999): we assume that the extent of environmental damage becomes known in the second period. Unlike Kennedy (1999), however, we allow for investment in the second period. Furthermore, we assume increasing rather than constant marginal environmental damage. Whereas it is always optimal to have all or none of the firms adopt the new technology if marginal damage is constant and all firms are the same, partial adoption may be optimal if marginal damage is increasing. Indeed, we shall mainly concentrate on the case of partial adoption. Our results are thus complementary to Kennedy's (1999).

The set-up of the paper is as follows. In the second section we develop a simple model that captures the essence of uncertain environmental damage and irreversible investments. In section 3, we analyze the impact of new scientific knowledge. The situation where uncertainty persists throughout the planning period is compared to the case where uncertainty is resolved in the course of the planning period. In the fourth section we address the impact of increased expected environmental damage. Finally, conclusions are drawn in section 5.

2 The model

In this section, we introduce the two building blocks of our analysis: the pollution damage functions and the abatement cost functions. We model time as discrete with an infinite horizon. For simplicity we ignore discounting.

Aggregate emissions E from firms are harmful to the environment. Damage from pollution only occurs in the period in which the polluting substance is emitted and is independent of the location of the firm. The relationship between aggregate emissions and environmental damage is constant over time, but there is uncertainty with respect to its exact nature. For a given level of emissions (E), damage $D^k = D(E, d_k)$ may either be high or low ($k = H, L$), depending on the value of the damage parameter d_k (with $d_L < d_H$). We make the following assumptions about the damage function:[4]

[4] Subscripts E (k) to D^k denote the partial derivative of the damage function with respect to E (d_k).

Condition 1 *Environmental damage is a thrice differentiable function* $D^k = D(E, d_k)$ *of emissions* E *and damage parameter* d_k, $k = H, L$. *The function satisfies:*

for $E = 0$*:*

a. $D^L = D^H = 0$ *and* $D_E^L = D_E^H = 0$*;*

for $E > 0$*:*

b. $D_E^k > 0$ *and* $D_{EE}^k > 0$

c. $D_k^k > 0$*, so that* $D(E, d_H) > D(E, d_L)$

d. $D_{Ek}^k > 0$*, so that* $D_E(E, d_H) > D_E(E, d_L)$

e. $\partial \left(D_{Ek}^k / D_{EE}^k \right) / \partial E > 0$*.*

Conditions 1a and 1b state that the damage function is upward sloping and convex, and goes through the origin. Conditions 1c and 1d indicate that environmental damage is increasing in the damage parameter and that an additional unit of the polluting substance is more damaging the higher the damage parameter. Condition 1e states that an increase in the damage parameter is assumed to be more harmful the higher the emission level. When drawing marginal damage MD^k as a function of emissions E, a marginal increase in the damage parameter (d_k) shifts the MD^k curve upward, say from MD_0^k to MD_1^k. Condition 1e implies that the horizontal distance between the MD_1^k and the MD_0^k curve increases with emissions E.

When it is unknown in a certain period whether the damage parameter is d_L or d_H, the probability that damage is low (high) is P $(1 - P)$. Expected damage then equals:

$$D^0(E, d_L, d_H) \equiv PD(E, d_L) + (1 - P)D(E, d_H). \tag{1}$$

Concerning firm behaviour, we focus on the pollution side of firm activity and ignore the output markets. There is a continuum of firms with mass 1. Aggregate emissions without abatement are normalized to unity. Firms can abate emissions using either a traditional or a new technology. Let n_j be the share of firms with the new technology under scenario j,[5] each abating $R_{j,t}$ in period t. A firm with the traditional technology abates $r_{j,t}$. Aggregate emissions are then:

$$E_{j,t} = (1 - n_j)\left[1 - r_{j,t}\right] + n_j\left[1 - R_{j,t}\right].$$

Total differentiation yields:

$$dE_{j,t} = -(1 - n_j)dr_{j,t} - n_j dR_{j,t} - (R_{j,t} - r_{j,t})dn_j. \tag{2}$$

Now we turn to the costs of the two technologies. The traditional technology only involves variable costs $C(r_{j,t})$. The new technology has fixed investment costs $F(f) > 0$, specific to firm f, and can run for two periods. Firms f are uniformly distributed on the unit interval from low to high sunk costs, and hence $F' \equiv \partial F/\partial f \geq 0$. When firms are identical, $F' = 0$ and $F(f) = \bar{F}$. When firms are heterogeneous, $F' > 0$. The new technology's per-period variable costs are given by $V(R_{j,t})$, which are assumed to be identical for all firms.[6] We assume the traditional technology's marginal cost function to be steeper than that of the new technology:

$$\begin{aligned} C'(0) &= V'(0) = 0 & (3)\\ C''(r) &> V''(R) > 0 \quad \text{for} \quad C'(r) = V'(R) > 0. & (4) \end{aligned}$$

Taken together, (3) and (4) imply:

$$C'(r) > V'(R) > 0 \qquad \text{for all } r = R > 0. \tag{5}$$

Thus, given the amount of emission reduction ($r = R$), the traditional technology's marginal abatement costs exceed those of the new technology: whereas the latter technology involves an (irreversible) investment, it has the advantage of lower variable abatement costs.

The government sets the tax rate or the number of tradeable permits at the beginning of each period, knowing that the new technology is available, and before firms have

[5] We define the scenarios at the end of this section.

[6] Of course, modelling firm heterogeneity in terms of differences in fixed investment costs is rather specific. It can be defended by arguing that either their installation costs or the resale value of their obsolete technologies (scrap value) may differ between firms. In any case, all results presented in this paper carry through when introducing firm heterogeneity with respect to their marginal abatement costs, but this line is not pursued for reasons of mathematical tractability.

made their investment decision. As Kennedy and Laplante (1999) and Requate and Unold (2001, 2003) have shown in their models, the first best can then be implemented[7,8] and is time-consistent. Note that this would not be the case if the government had set environmental policy without expecting the introduction of the new technology (Requate and Unold, 2001, 2003) or if firms could influence government policy (Kennedy and Laplante, 1999; Gersbach and Glazer, 1999).[9]

We shall analyze four scenarios $j, j = 0, H, L, U$. In scenario H (L), it is known from the outset that environmental damage is high (low). In scenario 0, it remains unclear whether environmental damage is high or low; no new information becomes available over time. In scenario U, it becomes known at the beginning of period 2 whether environmental damage is high or low. In all scenarios, we focus on interior solutions where both technologies are used: $0 < n_j < 1$.

3 The impact of new information

In this section, we analyze what happens to optimal policy design when uncertainty with respect to the environmental damage function is resolved. We do so by determining, in subsection 3.1, optimal policy in a situation where uncertainty persists throughout the planning period (scenario 0) and by determining, in subsection 3.2, optimal policy when the actual damage function is revealed at the beginning of the second period (scenario U). In subsection 3.3, we compare the two scenarios.

3.1 No new information

In this subsection we assume that no new information becomes available over time, so that the damage function is D^0, as defined in (1), in both periods.[10] We will derive the

[7] There is an exception, already noted by Requate and Unold (2003). The number of firms with the new technology is undetermined with taxation of identical firms.

[8] Milliman and Prince (1989) and Jung et al. (1996) claim that auctioned tradeable permits result in more adoption of the new technology than grandfathered tradeable permits. However, Requate and Unold (2003) demonstrate that adoption incentives are the same under grandfathering and auctioning when the grandfathered amount does not depend on the firm's technology choice.

[9] Biglaiser et al. (1995) and Laffont and Tirole (1996) also study time consistency problems.

[10] The analysis for an uncertain but constant environmental damage function (D^0) is analogous to the analysis in a certain world (that is, when the environmental damage function is known to be either D^L or D^H). That is why we shall use the general scenario subscript i, $i = 0, H, L$, in this subsection.

social optimum and see how it is implemented with environmental taxes and tradeable permits.

The regulator wishes to minimize cost from period one onwards. Let there be a stock of $m_{i,0}$ firms in the interval $[0; m_{i,0}]$ that installed the new technology in the previous period 0 (where $m_{i,0}$ can be zero). This investment is still productive in period one. Social costs consist of the traditional technology's variable costs, the fixed and variable costs associated with the new technology, and the environmental damage costs. Aggregate social costs are:

$$\begin{aligned}&\sum_{t=1}^{\infty}[(1-n_{i,t})C(r_{i,t})+n_{i,t}V(R_{i,t})] \\ &+\sum_{t=1}^{\infty}\left[q\int_{m_{i,t-1}}^{n_{i,t}}F(f)df+(1-q)\int_{0}^{m_{i,t}}F(f)df+D^i(E_{i,t},d_L,d_H)\right]\end{aligned} \tag{6}$$

with

$$q=\begin{cases}0 & \text{for } t=2,4,6,\cdots \\ 1 & \text{for } t=1,3,5,\cdots\end{cases}$$

In odd periods $t = 1, 3, 5, \cdots$, there is a stock of investment from the previous period by firms in $[0, m_{i,t-1}]$ and the firms in $[m_{i,t-1}, n_{i,t}]$ invest, so that in period t firms $[0, n_{i,t}]$ have the new technology. In even periods $t = 2, 4, 6, \cdots$, there is a stock of investment from the previous period by firms in $[m_{i,t-2}, n_{i,t-1}]$ and the firms in the interval $[0, m_{i,t}]$ invest. The total stock of firms with the new technology then equals:

$$n_{i,t} = m_{i,t} + n_{i,t-1} - m_{i,t-2} \tag{7}$$

Let us first determine the optimal abatement levels r_{opt} and R_{opt}, given the share n of firms with the new technology. Using (2), we find:

$$C'(r_{opt}) = V'(R_{opt}) = D^i_E \tag{8}$$

We can now derive:[11]

[11] All proofs are in the Appendix.

Proposition 1 *Let r_{opt} and R_{opt} be the optimal abatement levels according to (8). Then:*

a. $R_{opt} > r_{opt}$: Per-firm abatement with the new technology exceeds per-firm abatement with the traditional technology;

b. $R'_{opt} \equiv dR_{opt}/dr_{opt} > 1$: A change in per-firm abatement with the traditional technology is accompanied by a larger change in per-firm abatement with the new technology;

c. $dr_{opt}/dn < 0$: Abatement per firm is decreasing in the number of firms with the new technology;

d. $dE/dn < 0$: Emissions are decreasing in the number of firms with the new technology.

e. $\partial E(d_L, d_H, n)/\partial d_k < 0,\ k = L, H$: Emissions are decreasing in expected damage.

With respect to $n_{i,t}$, we find that it is optimal to have a constant stock n_i of firms with the new technology starting from when the inherited stock is below n_i. If $m_{i,0} < n_i$, the firms in the interval $[m_{i,0}, n_i]$ should invest in odd periods and the firms in $[0, m_{i,0}]$ firms in even periods. If $m_{i,0} > n_i$, it is optimal to have no investment in odd periods and investment of the firms in $[0, n_i]$ in even periods. Minimizing (6) with respect to $n_{i,t}$ starting in period 1 for $m_{i,0} < n_i$ and in period two for $m_{i,0} > n_i$ and substituting (2) and (7), we find:

$$\frac{1}{2}F(n_i) + V(R_i) - C(r_i) = (R_i - r_i)\, D^i_E \tag{9}$$

Given that (8) and (9) are the first order conditions for the multi-period model, we can write down single-period aggregate cost in a way that yields the same first order conditions. For odd periods ($t = 1, 3, 5, \cdots$) and $m_{i,0} < n_i$, single-period cost would be:

$$(1 - n_{i,t})C(r_{i,t}) + n_{i,t}V(R_{i,t}) + \frac{1}{2}\int_{m_{i,0}}^{n_i} F(f)df + D^i(E_{i,t}, d_L, d_H) \tag{10}$$

Half of the fixed investment cost is thus imputed to either period in which the investment is productive.

We now turn to the question how the number of firms investing and the amount abated per firm should adjust in response to a change in the (expected) damage parameter $d_k, k = H, L$. We find:

Proposition 2 *Let r_i and R_i be the optimal abatement levels and n_i the optimal share of firms with the new technology under scenario i, $i = 0, H, L$, according to (8) and (9). Then:*

a. *$dn_i/dd_k > 0$, $k = H, L$: The number of firms with the new technology is increasing in the damage parameter.*

b. *$sgn(dr_i/dd_k) = sgn\ F'$: With identical firms, the abatement level per firm does not respond to a change in the damage parameter. With heterogeneous firms, abatement per firm is increasing in the damage parameter.*

Thus, we find that the optimal abatement level is an increasing function of the (expected) damage at least when firms are not completely identical. The increase in revenue from adopting the new technology should equal the increase in sunk cost for the marginal firm.

With identical firms, however, there is no increase in sunk costs: $F' = 0$. Then society will be indifferent between investment or no investment by any single firm in the optimum. This will only be the case for a specific pair of abatement levels $(r_{i,s}, R_{i,s})$ defined by

$$\frac{1}{2}\bar{F} + V(R_{i,s}) - C(r_{i,s}) = (R_{i,s} - r_{i,s})\, D_E^i. \tag{11}$$

Thus, if firms are identical, changes in the damage parameters only affect the optimal number of firms with the new technology and leave the optimal abatement levels for each firm type unaffected. The optimal abatement levels are implicitly given by (8) and (11).

The optimum can be implemented with tradeable emission permits and taxes. The tax rate or permit price will be equal to marginal damage: $p_i = D_E^i$. Substituting this into (9), we see that the marginal firm is indifferent between the two technologies:

$$p_i r_i - C(r_i) = p_i R_i - V(R_i) - \frac{1}{2} F(n_i). \tag{12}$$

The LHS of (12) reflects the marginal firm's per-period net payoff when not investing. With taxation, the first term on the LHS denotes the saving on the tax bill. With permits, it denotes the revenues from selling (or not having to buy) r_i permits. The second term on the LHS of (12) denotes the cost of abating r_i. The RHS presents the marginal firm's per-period payoff when investing. These are equal to tax savings or the revenues from selling R_i permits, minus variable and fixed imputed per-period abatement cost.

The optimal taxation level and permit price move in the same direction as the optimal abatement levels. This can be seen from (8):

$$\frac{dp_i}{dr_i} = C''(r_i) > 0. \tag{13}$$

Together with Proposition 2b, this implies:

Corollary 1 $sgn(dp_i/dd_k) = sgn\ F'$: *With identical firms, the permit price or tax rate does not respond to a change in the damage parameter. With heterogeneous firms, the permit price or tax rate is increasing in the damage parameter.*

We have seen that the optimum is an equilibrium with taxation and tradeable permits. We shall now see under which circumstances it is the only equilibrium:

Proposition 3 *The social optimum is the unique equilibrium with taxation when firms are heterogeneous, but not when they are homogeneous. The social optimum is the unique equilibrium with tradeable permits combined with banking from period 1 if* $m_{i,0} < n_i$ *and from period 2 if* $m_{i,0} > n_i$.

Thus if firms are identical and the government cannot adjust the tax rate after firms have chosen a technology, taxation cannot be used to implement the optimum

(Requate and Unold, 2003). This is because, as we have seen in (11), the optimal abatement levels are independent of n_i. There is a unique tax rate $p_{i,s}$ that implements these abatement levels. Given this tax rate, all firms are indifferent between the two technologies. Thus, the number of firms with the new technology is undetermined. With heterogeneous firms, taxation can be used, because then the number of firms with the new technology is increasing in the tax rate.

The role of banking is to remove inefficient equilibria with different permit prices from one period to the next. We let banking start in the period from which the optimal permit price is constant.[12] Alternatively, as Kennedy (1999) has shown, banking could start from period 1, with government intervention in period 2 in the form of open market operations or expropriation.

3.2 Optimal policy when uncertainty is resolved in period 2

Let us now consider the case where uncertainty about the damage is resolved at the beginning of the second period. We shall call this scenario U, with the firms in the interval $[0, n_U]$ investing in period one. We assume from the outset that $n_L < n_U < n_H$; Proposition 5a will demonstrate that these inequalities actually apply.

We first need to establish which costs to include in the aggregate cost expression to be minimized. Obviously, all period 1 costs need to be included. When damage turns out to be low in period 2, the number of firms with the new technology is higher than optimal: $n_U > n_L$. We know from subsection 3.1 that optimal policy is then to have no investment in period 2 and investment by firms in $[0, n_L]$ in period 3. Setting n_U in period 1 does therefore not affect the optimal path from period 3 onwards, but it does affect period 2. Thus, all costs in period 2 with low damage should be included. When damage turns out to be high in period 2, the regulator can immediately implement the optimal stock of firms with the new technology n_H, since $n_H > n_U$. Setting n_U in period 1 then does not affect variable abatement cost or environmental damage

[12] As Phaneuf and Requate (2002) point out, banking reduces efficiency if the optimal permit price changes at a different rate than the interest rate. They contrast this efficiency loss with the efficiency gain that banking can provide when firms know more about the abatement costs than the government. This efficiency gain does not occur in our model, because the government knows just as much as the firms.

from period 2 onward. It does, however, affect fixed cost in period 2: The more firms invested in period 1, the less still need to invest in period 2. Analogous to (10), half of the fixed cost of the firms invested in period 2 should be imputed to that period.

The social welfare function can then be written as follows:

$$\int_0^{n_U} F(f)df + n_U V(R_{U,1}) + (1-n_U) C(r_{U,1}) + D^0(E_{U,1}, d_L, d_H) +$$
$$+P\left[n_U V(R_{U,2}) + (1-n_U) C(r_{U,2}) + D^L(E_{U,2}, d_L)\right] + \frac{1-P}{2}\int_{n_U}^{n_H} F(g)dg,$$

where $R_{U,1}$ ($r_{U,1}$) is abatement by a firm with the new (traditional) technology in period 1 and $R_{U,2}$ ($r_{U,2}$) is abatement by a firm with the new (traditional) technology in period 2.L (i.e. period 2 with low environmental damage).

The first order conditions for $r_{U,1}, R_{U,1}$, $r_{U,2}$ and $R_{U,2}$ simply state that marginal abatement costs should be equal to (expected) marginal damage, analogous to (8):

$$C'(r_{U,1}) = V'(R_{U,1}) = D_E^0(E_{U,1}, d_L, d_H) \tag{14}$$
$$C'(r_{U,2}) = V'(R_{U,2}) = D_E^L(E_{U,2}, d_L). \tag{15}$$

Assuming an interior solution, the first order condition with respect to n_U is:

$$\left(\frac{1+P}{2}\right) F(n_U) + V(R_{U,1}) - C(r_{U,1}) + D_E^0(E_{U,1}, d_L, d_H)\frac{\partial E_{U,1}}{\partial n_U} +$$
$$+P\left[V(R_{U,2}) - C(r_{U,2}) + D_E^L(E_{U,2}, d_L)\frac{\partial E_{U,2}}{\partial n_U}\right] = 0. \tag{16}$$

We will now see that the optimum can be implemented with tradeable permits as well as with taxation.[13] Equations (14) and (15) imply that the optimal permit prices or tax rates are equal to:

$$p_{U,1} = D_E^0(E_{U,1}, d_L, d_H) \tag{17}$$
$$p_{U,2} = D_E^L(E_{U,2}, d_L). \tag{18}$$

Substituting (17) and (18) into (16), we find:

$$[p_{U,1}(R_{U,1} - r_{U,1}) - (V(R_{U,1}) - C(r_{U,1}))] +$$
$$+P[p_{U,2}(R_{U,2} - r_{U,2}) - (V(R_{U,2}) - C(r_{U,2}))] - \left(\frac{1+P}{2}\right)F(n_U) = 0. \tag{19}$$

[13] As noted above, taxation of identical firms does not result in a unique equilibrium. The number of firms investing is undetermined from period 2 with high and from period 3 with low damage.

The first term in square brackets on the LHS of (19) represents first-period cost savings (gross of investment cost) when investing in the new technology. With the new technology, firms increase their abatement effort from $r_{U,1}$ to $R_{U,1}$, thus decreasing their tax base. With tradeable permits, each firm can sell (or does not have to buy) $R_{U,1}-r_{U,1}$ permits. The first-period benefits associated with investing are thus $p_{U,1}\left(R_{U,1}-r_{U,1}\right)$. However, the increase in abatement cost $V(R_{U,1})-C(r_{U,1})$ should also be taken into account. We will denote gross cost savings in period 1 by π_1. Similarly, the second term between square brackets represents gross cost savings π_L in period 2.L. Thus, (19) can be rewritten as:

$$\pi_1+P\pi_L-\frac{1+P}{2}F(n_U)=0. \tag{20}$$

Let π_H be gross savings from the investment in period 2.H. Adding $(1-P)(\pi_H-\frac{1}{2}F(n_U))$ on both sides of (20), the condition becomes:

$$\pi_1+P\pi_L+(1-P)\pi_H-F(n_U)=(1-P)\left(\pi_H-\frac{1}{2}F(n_U)\right). \tag{21}$$

The LHS of (21) denotes the marginal firm's cost savings derived from investing in period 1: sunk costs are $F(n_U)$, gross cost savings are π_1 in period 1 and π_L or π_H in period 2, with probability P and $1-P$ respectively. The RHS of (21) denotes the expected benefits of waiting until period 2. With probability P, environmental damage (and hence also the permit price or tax rate) is low, and investment is not profitable for the marginal firm. Then the firm does not invest and benefits are zero. With probability $1-P$, environmental damage is high, and the benefit in period 2 from investing is $\pi_H-\frac{1}{2}F(n_U)$. Thus, the marginal firm n_U will be indifferent between investing in period 1 and waiting until period 2, and tradable permits and taxation implement the optimum.

We have now seen that the optimum is an equilibrium outcome with taxation and tradeable permits. But it is somewhat more involved to prove the following proposition that it is the unique optimum:

Proposition 4 *In scenario U, the optimum is the unique equilibrium with taxation of heterogeneous firms and with tradeable permits combined with banking from period 2 (3) when damage is high (low).*

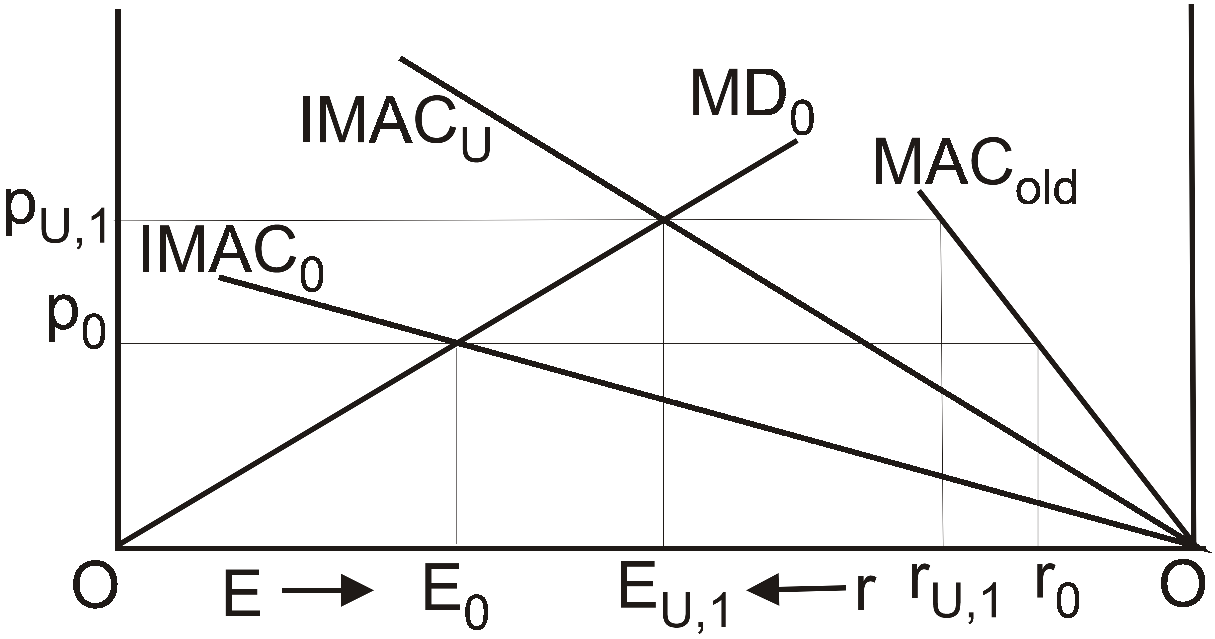

Figure 1: Comparing period 1 of scenario U and scenario 0

3.3 The implications of the arrival of new information

The impact of the arrival of information about actual marginal damage in period 2 can be established by comparing the two scenarios (denoted by subscripts 0 and U) as presented in the previous subsections.

Let us start the analysis with n_U firms investing. From (9) and (16) it follows that $n_L < n_U < n_0$. This is because, just looking at period 1, n_0 would be optimal, whereas n_L would be optimal for period 2.L. The actual number n_U of firms investing must be a compromise between the two.

Now let us compare period 1 of scenario U, where damage is not yet known, with scenario 0, where damage remains unknown throughout. Figure 1 illustrates the comparison. Note that, although this figure features linear marginal damage and abatement cost curves, our analysis is not limited to that case. The curve MD_0 depicts *expected* marginal damage in period 1. The $IMAC$ curves represent the industry's marginal abatement costs. We know that $n_U < n_0$: in scenario U there are less firms with the new technology which has the lower marginal abatement cost. Thus, the $IMAC_U$ curve lies above the $IMAC_0$ curve. It follows immediately that $E_{U,1} > E_0$ and $p_{U,1} > p_0$.

Also shown in Figure 1 is the MAC_{old} curve which represents the marginal abatement cost of the old technology. Abatement r by a firm with the old technology is measured from right to left on the horizontal axis. We see that $r_{U,1} > r_0$. Obviously, the same holds for the new technology: $R_{U,1} > R_0$. Thus, each firm type abates more in period 1 of scenario U, but total abatement is lower as there are fewer firms with the new technology.

We could draw a similar figure for the comparison of period 2 of scenario U in case damage turned out to be low, with scenario L where this is known from the outset. In this figure, $IMAC_L$ would lie above $IMAC_U$, and we would see that $E_{U,2} < E_L$, $p_{U,2} < p_L$, $r_{U,2} < r_L$ and $R_{U,2} < R_L$.

Summarizing, we have:

Proposition 5 *Comparing scenario U to the scenarios 0 and L:*

a. $n_L < n_U < n_0$;

b. $r_{U,1} > r_0$ *and* $r_{U,2} < r_L$*, and hence* $r_{U,1} > r_{U,2}$;

c. $E_{U,1} > E_0$ *and* $E_{U,2} < E_L$.

4 The impact of higher expected damage

Let us now analyze what happens if expected environmental damage increases in scenario U, where the true extent of environmental damage will become known at the beginning of period 2. The results for P and d_H are easily understood and will only be presented verbally here. An increase in the high-damage parameter d_H as well as a decrease in the probability P that damage will be low have the same qualitative consequences. The number of firms n_U with the new technology as well as first-period abatement per firm will rise. Since d_L has not changed, the increase in n_U will result in less abatement per firm in period 2.L (see Proposition 1c). Emissions in both periods will decline, in period 1 because expected environmental damage has increased, and in period 2.L since the increase in n_U has decreased aggregate marginal abatement cost (see Proposition 1d).

The comparative statics for the low-damage parameter d_L are more complicated:

Proposition 6 *The comparative statics with respect to the low-damage parameter d_L in scenario U are*

a. $dn_U/dd_L > 0$;

b. $dr_{U,1}/dd_L < (>)\ 0$ *for sufficiently homogeneous (heterogeneous) firms;*

c. $dr_{U,2}/dd_L > 0$;

d. $dE_{U,1}/dd_L < 0$ *and* $dE_{U,2}/dd_L < 0$.

Proposition 6b is the surprising part. At first sight, one might expect that a higher level of d_L would imply less emissions and a higher permit price or tax rate in both periods. Although this conjecture holds if uncertainty is never resolved (see subsection 3.1) or if the investment decision is perfectly reversible, the result does not always carry over to the case under consideration. With homogeneous firms, first-period abatement per type of firm should *decrease* when d_L rises. The intuition is as follows. Profits from investing in the new technology must remain constant to keep all firms indifferent between the two technologies. Indeed, this implies that only one of the abatement levels $r_{U,1}$ and $r_{U,2}$ can rise, and the other must decline. Proposition 6c states that $r_{U,2}$ will rise, as expected. But if $r_{U,2}$ rises with d_L, $r_{U,1}$ must decline.

We can also look at the result from another angle. Suppose it is already known in period 1 that the damage coefficient would be d_H. Then abatement in both periods would be $r_{i,s}$, as implicitly defined by (11) and (12). But now let there be a possibility that the damage coefficient turns out to be $d_L < d_H$ in period 2. Then we find $r_{U,1} > r_{i,s}$ and $r_{U,2} < r_{i,s}$. The larger d_L, the closer it gets to d_H, and therefore the abatement levels $r_{U,1}$ and $r_{U,2}$ get closer to $r_{i,s}$. Hence, $r_{U,1}$ has to decline and $r_{U,2}$ has to rise as d_L rises.

The story is different for heterogeneous firms. In this case, revenue from the new technology must rise in order to induce more firms to invest as the marginal firm's sunk costs are increasing with the share of firms investing. Then there may be room for $r_{U,1}$ to increase along with $r_{U,2}$.

The possible outcome that a higher d_L should result in a decrease in abatement per type of firm has direct implications for the socially optimal permit prices and tax rates. Combining Propositions 6b and 6c with (13), we find:

Corollary 2 *a.* $dp_{U,1}/dd_L < (>)0$ *if firms are sufficiently homogeneous (heterogeneous),*

b. $dp_{U,2}/dd_L > 0$.

Thus, a higher expected lower bound for the environmental damage will unambiguously translate into a higher tax rate in period 2, but may cause the tax rate in the first period to decrease if firms are sufficiently homogeneous in investment costs.

5 Conclusions

One of the main problems environmental policy makers are confronted with is the lack of accurate information concerning both the benefits and costs of environmental policy. More accurate information about environmental damage may become available at a future point in time when the abatement investments of today can still be used. When environmental damage turns out to be low, abatement investment has been too high in hindsight. However, the investment decision cannot be reversed.

We have analyzed the effects of an increase in the lower-bound estimate of environmental damage. Most results are standard. For example in period two, when uncertainty has been resolved, firms should abate more to reduce aggregate emissions; thus, the permit price should also be higher. Furthermore, more firms should adopt the new technology with its irreversible investment cost and lower marginal abatement cost than the traditional technology.

However, surprisingly we find that a higher expected lower bound may translate in a lower permit price or tax rate in period one, before the actual state of the world is revealed. The intuition is most readily seen for the case of identical firms. In this case, all firms should be indifferent between investing and not investing in the new technology. Since revenues from the new technology rise in period two, they should decline in period one. This means that the permit price must decline in period one.

If however, firms are heterogeneous in the costs of the new technology, those firms with the lowest costs will be the most willing to invest. That means that the marginal firm's investment costs are an increasing function of the share of firms adopting. Thus, the net revenues of installing an new technology should go up over the two periods in order to induce an additional firm to invest. Therefore, increased revenues in period two no longer necessarily imply that net revenues should decrease in period one.

If firms are sufficiently homogeneous, we can observe the perverse phenomenon of decreasing emissions and decreasing permit prices in period one. More importantly, when the government uses taxation, it should realize that the proper reaction to an increase in the lower-bound estimate of environmental damage may be to reduce the period one tax rate.

6 Appendix

6.1 Proof of Proposition 1

a. Follows from (5) and (8).

b. Totally differentiating $C'(r_{opt}) = V'(R_{opt})$, assumption (4) implies that:

$$R'_{opt} \equiv \frac{dR_{opt}}{dr_{opt}} = \frac{C''(r_{opt})}{V''(R_{opt})} > 1. \tag{22}$$

c. From $C'(r_i) = D^i_E$ (see (8)) with the aid of (22), we find (for a given d_k):

$$\frac{dr_{opt}}{dn} = -\frac{(R_{opt} - r_{opt})D^i_{EE}}{C''(r_{opt}) + (1 - n + nR'_{opt})D^i_{EE}} < 0. \tag{23}$$

d. Substituting (22) and (23) into (2), we find that $dE/dn < 0$.

e. From (8):

$$\frac{dr_i}{dd_k} = \frac{D^i_{Ek}}{C''} > 0 \qquad \frac{dR_i}{dd_k} = \frac{D^i_{Ek}}{V''} > 0$$

Substituting this into (2) yields $\partial E/\partial d_k < 0$.

6.2 Proof of Proposition 2

Total differentiation of (8) and (9) and using (22) yields (in matrix form):

$$\begin{bmatrix} C''(r_i) + (1 - n + R_i')\, D_{EE}^i & (R_i - r_i)\, D_{EE}^i \\ -(R_i - r_i)\, C''(r_i) & \frac{1}{2} F' \end{bmatrix} \begin{bmatrix} dr_i \\ dn_i \end{bmatrix} = \begin{bmatrix} D_{Ek}^i \\ 0 \end{bmatrix} dd_k.$$

Propositions 1a and 1b imply that the determinant of the Hessian (referred to A_i) is strictly positive. The comparative statics for n_i and r_i are:

$$\begin{aligned} \frac{dn_i}{dd_k} &= \frac{1}{A_i} D_{Ek}^i\, (R_i - r_i)\, C''(r_i) > 0 \\ \frac{dr_i}{dd_k} &= \frac{1}{2} \frac{F'}{A_i} D_{Ek}^i \geq 0. \end{aligned}$$

The inequalities follow from Condition 1d, (4), (5) and Propositions 1a and 1b.

6.3 Proof of Proposition 3

6.3.1 Taxation and homogeneous firms

To prove that there is no unique equilibrium in this situation, let us look at the case with $m_{i,0} = 0$. The proof for other cases is similar. The regulator sets the tax rate at p_i in period 1, hoping that n_i firms will invest. Let $n_a < n_i$ firms invest instead. Then in period 2, the regulator will again set the tax rate at p_i, hoping that an additional $n_i - n_a$ firms will invest. With the tax rates at p_i in both periods 1 and 2, firms are indifferent between investing and not investing in period 1, and thus any $n_a \leq n_i$ firms investing in period 1 is an equilibrium. Indeed, any stock $n_a \leq n_i$ firms with the new technology in any period is an equilibrium. The stock cannot exceed n_i, however, because that would trigger a tax rate below p_i in the next period.

6.3.2 Taxation and heterogeneous firms

First, consider the case $m_{i,0} > n_i$. In period 1, the regulator will set the tax rate at the level that is optimal given investment by $m_{i,0}$ firms. By Proposition 1c and (13), the tax rate in period 1 will be below p_i. No firms are supposed to invest in period 1. Suppose that, instead, the firms in $[m_{i,0}, n_a]$ do invest. Then there are two possibilities, either $n_a - m_{0,i} > n_i$ or $n_a - m_{0,i} < n_i$. In period 2, when $n_a - m_{0,i} > n_i$, the regulator will set the tax rate below p_i at the optimal level given investment by $n_a - m_{0,i}$ firms.

When $n_a - m_{0,i} < n_i$, it is optimal for the firms in $[0, n_b]$, $n_b < m_{0,i}$, and in $[n_b, n_i]$ to invest in periods 2 and 3, respectively. The tax rate in period 2 will be below p_i, so that firm $n_b < n_i$ will be indifferent between investing and not investing, given the tax rate in period 2 and a tax rate of p_i in period 3. In both cases, whether $n_a - m_{0,i}$ is above or below n_i, the period 2 tax rate will be below p_i. With the tax rates below p_i in both periods 1 and 2, investment is not profitable for firm n_i, let alone for the firms in $[m_{i,0}, n_a]$. The rest of the proof for $m_{i,0} > n_i$ is analogous to the proof for $m_{i,0} < n_i$.

Now consider the case $m_{i,0} < n_i$. In period 1, the regulator sets the tax rate at p_i, hoping that the firms in $[m_{i,0}, n_i]$ will invest. Let the firms in $[m_{i,0}, n_a]$ actually invest. First, consider $n_a < n_i$. Then in period 2, the regulator will again set the tax rate at p_i, hoping that the firms in $[0, m_{0,i}]$ and in $[n_a, n_i]$ will invest. With the tax rate at p_i in both periods 1 and 2, all firms in $[m_{i,0}, n_i]$ will want to invest in period 1. For $n_a > n_i$, we can use the reasoning from the case $m_{i,0} > n_i$ to show that the period 2 tax rate will be below p_i. With the tax rates at p_i in period 1 and below p_i in period 2, investment in period 1 is not profitable for firm n_i, let alone for the firms in $[m_{i,0}, n_a]$.

6.3.3 Tradeable permits and homogeneous firms

First, consider the case $m_{i,0} < n_i$. In period 1, the regulator issues E_i permits, hoping that $n_i - m_{i,0}$ firms will invest. Let $n_a < n_i - m_{i,0}$ firms invest in period 1. Without banking, there can be a cycle with permit price $p_a > p_i$ in odd and $p_b < p_i$ in even periods, until the number of firms investing in an odd period drops to zero. In the next period, a new cycle can start. To avoid this cycle and to make the optimum the unique equilibrium, the regulator could allow banking of permits. Firms would then bank permits from period 2 to 3, which unravels the cycle. The unique equilibrium then features the same permit price p_i in all periods.

Now, consider the case $m_{i,0} > n_i$. In period 1, the regulator issues the optimal amount of permits for investment by $m_{i,0}$ firms. Permit price will be below p_i and no firms are supposed to invest. Now let $n_a > 0$ firms invest, so that the period 1 permit price will be even further below p_i. There are two cases to consider: $n_a < n_i$ and $n_a > n_i$. When $n_a < n_i$, the regulator issues E_i permits in period 2 and allows banking. Then permit price in period 2 will be p_i. In period 2, when $n_a > n_i$, the government sets the optimal amount of permits for investment by n_a firms and permit price will be below p_i. With permit prices below p_i in period 1 and at or below p_i in period 2, investment is not profitable in period 1.

6.3.4 Tradeable permits and heterogeneous firms

When $m_{i,0} < n_i$, there will be banking from period 1 and the unique equilibrium is the optimum, with a permit price of p_i in all periods. If banking were not allowed, there could be other equilibria with cycles, as we saw with homogeneous firms.

Now, consider the case $m_{i,0} > n_i$. In period 1, the regulator issues the optimal amount of permits for investment by $m_{i,0}$ firms. Permit price will be below p_i and no firms are supposed to invest. Now let the firms in $[m_{i,0}, n_a]$ invest, so that the period 1 permit price will be even further below p_i. There are two cases to consider: $n_a - m_{i,0} < n_i$ and $n_a - m_{i,0} > n_i$. When $n_a - m_{i,0} < n_i$, the regulator issues E_i permits in period 2 and allows banking. Then permit price in period 2 will be p_i. In period 2, when $n_a - m_{i,0} > n_i$, the government sets the optimal amount of permits for investment by n_a firms and permit price will be below p_i. With permit prices below p_i in period 1 and at or below p_i in period 2, investment in period 1 is not profitable for firm n_i, let alone for the firms in $[m_{i,0}, n_a]$.

6.4 Proof of Proposition 4

6.4.1 Taxation and heterogeneous firms

At the beginning of period 1, the regulator sets the tax rate at $p_{U,1}$, hoping that the firms in $[0, n_U]$ will invest. Let the firms in the interval $[0, n_a]$ invest.

If $n_a < n_U$ firms invest in period 1, the regulator will set the tax rate above $p_{U,2}$ in period 2.L. If $n_a > n_L$, the tax rate will be between $p_{U,2}$ and p_L, according to the optimum with n_a firms with the new technology. If $n_a < n_L$, the regulator will set the tax rate at p_L, hoping that the firms $[n_a, n_L]$ will invest in period 2.L. With the tax rate at $p_{U,1}$ in period 1 and above $p_{U,2}$ in period 2.L, it is optimal for all firms in the interval $[0, n_U]$ to invest.

If $n_a > n_U$ firms invest in period 1, the regulator sets the tax rate below $p_{U,2}$ in period 2.L, according to the optimum with investment by n_a firms. This tax rate is below $p_{U,2}$. With the tax rate at $p_{U,1}$ in period 1 and below $p_{U,2}$ in period 2.L, investment is not profitable for firm n_U, let alone for the firms in the interval $[n_U, n_a]$. We conclude that investment by the firms $[0, n_U]$ is the unique equilibrium.

6.4.2 Tradeable permits and homogeneous firms

At the beginning of period 1, the regulator issues $E_{U,1}$ permits, hoping that n_U firms will invest. Let a total of n_a firms invest. If $n_a > n_U$ firms invest in period 1, the permit price in period 1 will be below $p_{U,1}$. In period 2.L, the regulator will issue the amount of permits that is optimal given investment by n_a firms. The permit price will be below $p_{U,2}$. With the permit price below $p_{U,1}$ in period one and below $p_{U,2}$ in period 2.L, investment is not profitable.

If $n_a < n_U$ firms invest in period 1, the permit price in period 1 will exceed $p_{U,1}$. For these n_a firms to be indifferent between investing and not investing, the permit price in period 2.L must be below $p_{U,2}$. This can only happen if there are $n_b > 0$ firms investing in period 2.L. Now there are two possibilities: either $n_b > n_L$ or $n_b < n_L$. In period 3.L, when $n_b > n_L$, the regulator issues the optimal amount of permits given investment by n_b firms. Permit price in period 3.L will be below p_L. With permit prices below $p_{U,2} < p_L$ in period 2.L and below p_L in period 3.L, investment is not profitable in period 2.L. When $n_b < n_L$, the regulator issues E_L in period 3.L and allows banking. The unique equilibrium has $n_L - n_b$ firms investing and a permit price of p_L in period 3.L. With permit prices below $p_{U,2} < p_L$ in period 2.L and at p_L in period 3.L, investment is not profitable in period 2.L. Since investment in period 2.L is needed to sustain $n_a < n_U$ firms investing in period one, the latter is not an equilibrium.

6.4.3 Tradeable permits and heterogeneous firms

At the beginning of period 1, the regulator issues $E_{U,1}$ permits, hoping that the firms in the interval $[0, n_U]$ will invest. Let the firms in $[0, n_a]$ invest. If $n_a > n_U$ firms invest in period 1, the permit price in period 1 will be below $p_{U,1}$. In period 2.L, the regulator will issue the amount of permits that is optimal given investment by n_a firms. The permit price will be below $p_{U,2}$. With permit prices below $p_{U,1}$ in period 1 and below $p_{U,2}$ in period 2.L, investment is not profitable for firm n_U, let alone for the firms in the interval $[n_U, n_a]$.

If $n_a < n_U$ firms invest in period 1, the permit price in period 1 will exceed $p_{U,1}$. For firm n_a to be indifferent between investing and not investing, the permit price in period 2.L must be below $p_{U,2}$. This can only happen when firms in the interval $[n_a, n_b]$, with $n_b > n_L$, invest in period 2.L.

Now there are two possibilities: either $n_b - n_a > n_L$ or $n_b - n_a < n_L$. In period 3.L, when $n_b - n_a > n_L$, the regulator issues the optimal amount of permits given investment by $n_b - n_a$ firms. Permit price in period 3.L will be below p_L. When $n_b - n_a < n_L$, it is optimal to have the firms in $[0, n_c]$ investing in period 3.L, with $n_c < n_L$. From period 4.L onwards, it is optimal to have a stock of n_L firms with the new technology. Thus, the regulator issues E_L permits in period 4.L and allows banking. The unique equilibrium has the firms in $[n_c, n_L]$ investing and a permit price of p_L in period 4.L. In period 3.L, permit price will be below p_L so that firm $n_c < n_L$ is indifferent between investing and not investing in period 3.L. Thus, for $n_b - n_a > n_L$ as well as for $n_b - n_a < n_L$, we find that permit price in period 3.L is below p_L.

With permit prices below $p_{U,2} < p_L$ in period 2.L and below p_L in period 3.L, investment in period 2.L would not be profitable for firm n_L, let alone for firm $n_b > n_L$. Since firm n_b should be indifferent between investing and not investing in period 2.L to sustain $n_a < n_U$ firms investing in period 1, the latter is not an equilibrium.

6.5 Proof of Proposition 6

We totally differentiate the first order conditions (14) to (16), making use of (22):

$$\begin{bmatrix} C''(r_{U,1}) + E'_{U,1}D^0_{EE} & 0 & \rho_{U,1}D^0_{EE} \\ 0 & C''(r_{U,2}) + E'_{U,2}D^{L2}_{EE} & \rho_{U,2}D^{L2}_{EE} \\ -\rho_{U,1}C''(r_{U,1}) & -P\rho_{U,2}C''(r_{U,2}) & \left(\frac{1+P}{2}\right)F' \end{bmatrix} \begin{bmatrix} dr_{U,1} \\ dr_{U,2} \\ dn_U \end{bmatrix} = \begin{bmatrix} PD^{L1}_{EL} \\ D^{L2}_{EL} \\ 0 \end{bmatrix} dd_L \tag{24}$$

where $E'_{U,t} \equiv 1 - n_U + n_U R'_{U,t} > 0$ and $\rho_{U,t} \equiv R_{U,t} - r_{U,t} > 0,\ t = 1, 2.$ The determinant of the system (labelled A_U) is unambiguously positive. The following holds:

a. Applying Cramer's rule to (24), we find $dn_U/dd_L > 0$.

b. The comparative statics for $r_{U,1}$ are:

$$\begin{aligned}\frac{dr_{U,1}}{dd_L} &= \frac{1}{A_U}\left[PF'D_{EL}^{L1}\left(\frac{1+P}{2}\right)\left(C''(r_{U,2})+E'_{U,2}D_{EE}^{L2}\right)\right] \\ &\quad -\frac{P\rho_{U,2}C''(r_{U,2})}{A_U}\left[\rho_{U,1}D_{EL}^{L2}D_{EE}^{0}-P\rho_{U,2}D_{EL}^{L1}D_{EE}^{L2}\right].\end{aligned} \tag{25}$$

The first term between square brackets on the RHS of this equation is zero or positive depending on whether $F' = 0$ or $F' > 0$. The second term between square brackets is unambiguously positive. To determine its sign, first note that $\rho_{U,1} \equiv R_{U,1} - r_{U,1} > R_{U,2} - r_{U,2} \equiv \rho_{U,2}$ by Proposition 1b and Corollary 2a. Furthermore, we can prove that:

$$D_{EL}^{L2}D_{EE}^{0} > PD_{EL}^{L2}D_{EE}^{L1} > PD_{EL}^{L1}D_{EE}^{L2}. \tag{26}$$

The first inequality is obvious from (1). The second inequality holds by Condition 1e combined with $E_{U,2} > E_{U,1}$. The latter inequality follows from Proposition 1e and $D^0(E, d_L, d_H) > D^L(E, d_L)$. Thus, $dr_{U,1}/dd_L < 0$ for homogeneous as well as for slightly heterogeneous firms and $dr_{U,1}/dd_L > 0$ for very heterogeneous firms.

c. Using (26), the comparative statics of $r_{U,2}$ with respect to d_L are unambiguously positive.

d. Substituting (22) into (2):

$$\frac{dE_{U,t}}{dd_L} = -(1 - n + nR'_{U,t})\frac{dr_{U,t}}{dd_L} - (R_{U,t} - r_{U,t})\frac{dn_U}{dd_L}. \tag{27}$$

We immediately see that $dE_{U,2}/dd_L < 0$ since $dr_{U,2}/dd_L > 0$ by Proposition 6c and $dn_U/dd_L > 0$ by Proposition 6a. Inserting the results from Propositions 6a and 6b into (27), we can derive $dE_{U,1}/dd_L$:

$$\begin{aligned}\frac{dE_{U,1}}{dd_L} &= \frac{-PE'_{U,1}}{A_U}\left[\begin{array}{c}\left[F'D_{EL}^{L1}\left(\frac{1+P}{2}\right)\left(C''(r_{U,2})+E'_{U,2}D_{EE}^{L2}\right)\right] \\ +P\left(\rho_{U,2}\right)^2 C''(r_{U,2})D_{EL}^{L1}D_{EE}^{L2}\end{array}\right] \\ &\quad -P\frac{\rho_{U,1}}{A_U}\left[\begin{array}{c}\left[D_{EL}^{L1}\rho_{U,1}C''(r_{U,1})\left(C''(r_{U,2})+E'_{U,2}D_{EE}^{L2}\right)\right] \\ +\left[D_{EL}^{L2}\rho_{U,2}\left(C''(r_{U,2})\right)^2\right]\end{array}\right] < 0.\end{aligned}$$

References

[1] Arrow, K.J. and A.C. Fisher (1974), "Environmental preservation, uncertainty, and irreversibility", Quarterly Journal of Economics 88: 312-319.

[2] Biglaiser, G., J.K. Horowitz and J. Quiggin (1995), "Dynamic pollution regulation", Journal of Regulatory Economics 8: 33-44.

[3] Dixit, A.K. and R.S. Pindyck (1994), "Investment under uncertainty," Princeton: Princeton University Press.

[4] Dosi, C. and M. Moretto (1997), "Pollution accumulation and firm incentives to accelerate technological change under uncertain private benefits", Environmental and Resource Economics 10: 285-300.

[5] Gersbach, H. and A. Glazer (1999), "Markets and regulatory hold-up problems", Journal of Environmental Economics and Management 37: 151-164.

[6] Hanemann, W.M. (1989), "Information and the concept of option value", Journal of Environmental Economics and Management 16: 23-37.

[7] Heal, G. and B. Kriström (2002), "Uncertainty and climate change", Environmental and Resource Economics 22: 3-39.

[8] Henry, C. (1974), "Investment decisions under uncertainty: The 'irreversibility effect"', American Economic Review 64: 1006-1012.

[9] Jaffe, A.B., R.G. Newell and R.N. Stavins (2002), "Environmental policy and technological change", Environmental and Resource Economics 22: 41-69.

[10] Jou, J-B (2001), "Environment, asset characteristics, and optimal effluent fees", Environmental and Resource Economics 20: 27-39.

[11] Jung, C., K. Krutilla and R. Boyd (1996), "Incentives for advanced pollution abatement technology at the industry level: An evaluation of policy alternatives", Journal of Environmental Economics and Management 30: 95-111.

[12] Kennedy, P.W. (1999), "Learning about environmental damage: Implications for emissions trading", Canadian Journal of Economics 32: 1313-1327.

[13] Kennedy, P.W. and B. Laplante (1999), "Environmental policy and time consistency: Emission taxes and emissions trading", in: E. Petrakis, E.S. Sartzetakis and A. Xepapadeas (eds), Environmental Regulation and Market Power: Competition, Time Consistency and International Trade, Edward Elgar, Cheltenham (UK): 116-144.

[14] Kolstad, C.D. (1996a), "Fundamental irreversibilities in stock externalities", Journal of Public Economics 60: 221-233.

[15] Kolstad, C.D. (1996b), "Learning and stock effects in environmental regulation: The case of greenhouse gas emissions", Journal of Environmental Economics and Management 31: 1-18.

[16] Laffont, J.J. and J. Tirole (1996), "Pollution permits and environmental innovation", Journal of Public Economics 62: 127-140.

[17] Milliman, S.R. and R. Prince (1989), "Firm incentives to promote technological change in pollution control", Journal of Environmental Economics and Management 17: 247-265.

[18] Petrakis, E. (1999), "Diffusion of abatement technologies in a differentiated industry", in: E. Petrakis, E.S. Sartzetakis and A. Xepapadeas (eds), Environmental Regulation and Market Power: Competition, Time Consistency and International Trade, Edward Elgar, Cheltenham (UK), 162-174.

[19] Phaneuf, D.J. and T. Requate (2002), "Incentives for investment in advanced pollution abatement technology in emission permit markets with banking", Environmental and Resource Economics 22: 369-390.

[20] Pindyck, R.S. (2000), "Irreversibility and the timing of environmental policy", Resource and Energy Economics 22: 233-259.

[21] Requate, T. (1995), "Incentives to adopt new technologies under different pollution-control policies", International Tax and Public Finance 2: 295-317.

[22] Requate, T. (1998), "Incentives to innovate under emission taxes and tradeable permits", European Journal of Political Economy 14: 139-165.

[23] Requate, T. and W. Unold (2001), "On the incentives created by policy instruments to adopt advanced abatement technology if firms are asymmetric", Journal of Institutional and Theoretical Economics 157: 536-554.

[24] Requate, T. and W. Unold (2003), "Environmental policy incentives to adopt advanced abatement technology: Will the true ranking please stand up?", European Economic Review 47: 125-146.

[25] Saphores, J-D M. and P. Carr (2000), "Real options and the timing of implementation of environmental limits under ecological uncertainty", in: M. Brennan and L. Trigeorgis (eds), Project Flexibility, Agency, and Competition: New Developments in the Theory and Application of Real Options, Oxford University Press, Oxford.

[26] Viscusi, W.K (1988), "Irreversible environmental investments with uncertain benefit levels", Journal of Environmental Economics and Management 15: 147-157.