Investment and emission control under technology and pollution externalities

(Original title: Technology diffusion, abatement cost, and transboundary pollution)

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Classification: Q50, H87, D70

Keywords: International environmental agreement; pollution abatement costs; endogenous technological change.

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This paper studies incentives to develop advanced pollution abatement technology when technology may spillover across agents and pollution abatement is a public good. We are motivated by a variety of pollution control issues where solutions require the development and implementation of new pollution abatement technologies. We show that at the Nash equilibrium of a simultaneous-move game with R&D investment and emission abatement, whether the free rider effect prevails and under-investment and excess emissions occur depends on the degree of technology spillovers and the effect of R&D on the marginal abatement costs. There are cases in which, contrary to conventional wisdom, Nash equilibrium investments in emissions reductions exceed the first-best case.

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1 Introduction

Controlling pollution is a public good in many cases, within or across countries, where effective control requires the development of a new technology. The control of ozone-depleting chlorofluorocarbons (CFCs) is a notable example where the removal required a novel technological development (i.e. less harmful substitutes for CFCs, Barrett 1992); the control of sulfur dioxide (SO_2) emissions that caused acid rain also had these characteristics, and the last two decades have seen many technological changes in the capturing of SO_2 emissions (Popp 2006). A current example is the release of greenhouse gases causing climate change, as is the emission of nitrogen oxides (NO_x), which contribute to acid rain, climate change and acidification of water bodies. Development of new technologies would be necessary for mitigating not only air pollution but water pollution and hazardous waste. Pollution of coastal water, and resulting damages to the coastal ecosystems, caused by runoffs of sediments and fertilizers is an example of non-air pollution where technology innovation for abatement is called for (National Research Council 2000, Chapter 9). It is for this reason—the necessity of technology innovation—that researchers argue that "understanding the interactions between environmental policy and technology may have quantitatively important consequences in the context of cost-benefit or cost-effectiveness analyses of such policies" (Popp et al. 2009).

In the context of pollution control where pollution generates negative externalities, We examine how the effect of technological innovation on the cost structure of emission abatement influences the agents' incentives to reduce emissions and to invest in R&D in new technologies. To analyze these issues, we use a simultaneous-move game of emissions reduction and R&D investments where each agent acts noncooperatively. We hope that the intuitions we develop here can be valuable in managing the R&D process and structuring collective action or international agreements for pollution control.

Most studies on emission control and technological innovation predict that scenarios without policy intervention involve excessive emissions and insufficient R&D relative to the first best levels. It is not widely recognized that a crucial assumption behind this prediction is that the marginal abatement cost decreases as technology improves. In fact this need not be the case: we provide examples of technological changes which imply smaller total abatement costs but larger marginal abatement costs. Using a simultaneous-move game of emissions reduction and R&D investments, we find that the equilibrium R&D investment can be larger than the first best level in these examples.

In the context of transboundary pollution, technological innovation is often induced by an international environmental agreement (IEA). In some cases, IEAs explicitly encourage the signatories to cooperate in R&D.[1] Several studies have examined how technology spillovers influence countries' cooperation in providing global public goods.[2] Carraro and Siniscalco (1997) analyze the stability of IEAs assuming that the signatories conduct R&D to develop a cleaner technology which is unavailable to non-signatories. Buchner et al. (2002) study the stability of climate change mitigation cooperation across countries when technology spillovers within cooperating countries are larger than spillovers from cooperating countries to non-cooperating countries. Barrett (2003) raises two questions about their approach (pp.309-310). First, it is often difficult to prevent technology diffusion once new technology is developed. Second, given that a cleaner technology is developed and signatories' environmental damage is increasing in non-signatories' emissions, the signatories may have an incentive to allow the non-signatories to use the cleaner technology so that the global emissions decline. Barret (2003) also argues that no existing IEAs prevent the non-signatories from using new technology developed by the signatories. For example, the Montreal Protocol requires that parties cooperate in promoting R&D for a technology that reduces controlled substances, where non-parties are allowed easy access to new technologies by the parties (Barret 2003, pp.309-10.) Indeed, there is a stronger argument against the idea that new technologies will not spill over: this is that the companies that develop them will want to sell them worldwide as part of a profit-maximization strategy. General Electric is aggressively promoting its carbon capture and storage technologies worldwide, though they were developed in the U.S.

To investigate agents' incentive for emission control and investments, we consider a simultaneous-move game where the agents choose investments and emissions simultaneously

[1] Examples include a six-country pact for developing technology to reduce greenhouse gas emissions. See "Vision Statement of Australia, China, India, Japan, the Republic of Korea, and the U.S. for a New Asia-Pacific Partnership on Clean Development and Climate," available at http://www.state.gov/g/oes/rls/fs/50335.htm.

[2] Heal (1993) and Barrett (2003) argue that abatement efforts and technology change in one country may reduce the marginal abatement costs in other countries and the first-best outcome may be supported once a sufficient number of countries adopt higher environmental standards.

when both technology and pollution spill over across agents. We find the following (see Table 1).

1. If each agent's marginal abatement cost is decreasing in R&D investment, then the Nash equilibrium investments are lower and the equilibrium emissions are larger than the first-best levels. This result holds regardless of the degree of technology spillovers among agents. This is the "conventional wisdom" case.

2. If the marginal abatement costs are increasing in investment, then the equilibrium results in over-(under-)investment when the degree of spillovers is small (large) enough. With large technology spillovers, emissions may be less than in the first best case. This case is contrary to conventional wisdom.

The first point is consistent with Golombek and Hoel (2004), who have the same finding under the assumptions listed above. The second point implies that whether the first claim holds depends on the relationship between R&D and the marginal abatement costs. Section 2 discusses cases in which marginal abatement costs may increase under a new technology.

Intuitively we can see why the movement of marginal abatement costs (MACs) is important. Suppose that technological development leads to an abatement technology with lower fixed and higher variable costs, and lower average costs—we will suggest below that this accurately describes one of the main technologies now being developed, that of carbon capture and storage. Then the lower fixed costs have an income effect which will typically lead to the choice of more abatement. However, the higher MAC produces a substitution effect that acts in the opposite direction. Higher MAC also implies that the marginal reduction in abatement costs due to investment is larger when emissions are larger. When technology spillovers are small, this fact implies that both the equilibrium investment and the equilibrium emissions are larger than the socially optimal levels. When technology spillovers are large, however, each agent's incentive for investment is smaller. In such a situation it is not clear whether the outcome will be more or less abatement. This is true for both the socially optimal allocation and the Nash equilibrium allocation, but it is stronger for the first best case and so tends to reduce abatement more, reduce emissions less, in this case. This opens up the possibility that the equilibrium emissions may be less than the first best, as equilibrium abatement is reduced less. We show below that this can happen when spillovers are large: large spillovers tend of course to counteract the standard arguments about free riders and public goods. Large spillovers provide income effects to all agents, similarly to lower fixed costs. This explains why we find counterintuitive outcomes with small income effects.

[Table 1]

The next section discusses examples of technologies where the marginal abatement cost may decrease or increase as a result of technology innovation. Section 3 describes the assumption of our analysis, the result, and discussions regarding alternative assumptions. Section 4 concludes the paper with policy implications.

2 Technology innovation and marginal abatement costs

The relationship between marginal abatement costs and R&D is central to some of our results. We expect, of course, that abatement costs will fall as a result of successful R&D—that is in effect the definition of success in R&D. Presumably we mean the total cost of attaining a given level of abatement falls, but this leaves open the impact of R&D on the fixed and variable costs of reducing emissions. In principle, successful R&D can introduce a new technology whose cost structure is totally different from that of the current technology. The current technology may for example have high fixed and low variable costs, whereas the new one has low fixed costs and high variable costs. In this case the total and average costs would be lower but the marginal abatement cost might be higher with the new technology. These issues are discussed to some degree in Baker et al. (2006, 2008), who consider the effect of uncertainty about the costs of climate change on the optimal spending on R&D: they find that the abatement cost curve can change in many different ways as a result of R&D, depending on the parameters of the model. Bauman (2003) and Brechet and Jouvet (2006) also present theoretical models which demonstrate that the marginal abatement cost may be higher with new technology. *The Economics of Climate Change* (Stern Review, 2006) also notes that "step-change improvements in a technology might accelerate progress [of declining marginal costs], while constraints such as the availability of land or materials could result in increasing marginal costs" (Executive Summary, p.xx).

Researchers are currently investigating many different technologies for CO2 abatement. Integrated combined cycle coal gasification (ICCCG) with carbon capture and storage is one possibility: coal combustion with cryogenic oxygen and carbon capture and storage is another, and the use of renewable energy sources and nuclear power represent yet more alternatives. If we think of renewable energy and nuclear as the current abatement technologies, and ICCCG with C-capture and storage as a possible new technology, then the change in cost structures in going from the old to the new technologies is instructive. Renewable energy sources and nuclear have high fixed costs but almost no variable costs, so that the marginal cost of abatement along this route is close to zero even though the average is high. ICCCG with C-capture and storage, by contrast, would have high marginal costs: each ton of CO2 has to be captured (perhaps $5 per ton) and then transported (perhaps $10 per ton) and stored (perhaps $5 per ton). We would not use this technology unless its average cost were less than renewables, but if we used it we would face a higher marginal cost.[3]

3 A game with pollution and technology externalities

3.1 Assumptions, the optimal outcome, and the symmetric Nash equilibrium

Suppose N agents choose R&D investments and emissions for developing abatement technology. Let $(k_i, e_i) \geq 0$ be agent i's investment and emissions choice. Agent i's cost of investing k_i is given by $G(k_i) \geq 0$ where $G' > 0, G'' \geq 0$.[4] When the agents' investment profile is $k = (k_1, \ldots, k_N)$, agent i's cost of reducing emissions from its status-quo level $\bar{e} > 0$ to a level $e_i \geq 0$ is given by $C(e_i, z_i(k)) \geq 0$ where

$$z_i(k) = k_i + \lambda \sum_{j \neq i} k_j.$$

The function z_i represents the effective amount of abatement capital available to agent i given investment profile k. The exogenous parameter $\lambda \in [0, 1]$ represents the extent of innovation spillovers across agents. There is no technology diffusion and R&D is a private good if $\lambda = 0$. With complete spillovers, λ is equal to one. The abatement cost function

[3] We are grateful to Klaus Lackner for an instructive discussion of these issues.

[4] We have $G(k) = k$ provided that pollution control costs, damages, and investment costs are measured with the same metric. We have $G'' > 0$ if there is inefficiency in using resources for investment. We thank a referee for clarifying the role of function G.

C is twice continuously differentiable and convex with $C_e < 0, C_z < 0, C_{ee} > 0, C_{zz} > 0$ for all $e < \bar{e}$. (Subscripts stand for partial derivatives.) We assume C_{ez} is positive, zero, or negative. The marginal abatement cost $-C_e$ is decreasing in investment if $C_{ez} > 0$. Given total emissions $E = \sum_j e_j$, agent i's damage is $D(E) \geq 0$ where $D' > 0$ and $D'' > 0$.

We assume that the agents choose investment and emissions simultaneously. The main result of the paper will hold if the agents choose investment and emissions sequentially (i.e. they choose investment simultaneously first, and then emissions simultaneously).

The first-best investment emission and allocation $\{k_i^*, e_i^*\}$ minimizes the social cost of emissions $\sum_i [G(k_i) + C(e_i, z_i(k)) + D(E)]$. The first order condition for an interior solution is

$$G'(k_i^*) + C_z(e_i^*, k_i^* + \lambda \textstyle\sum_{j \neq i} k_j^*) + \sum_{j \neq i} \lambda C_z(e_j^*, k_j^* + \lambda \sum_{l \neq j} k_l^*) = 0,$$

$$C_e(e_i^*, k_i^* + \textstyle\sum_{j \neq i} k_j^*) + ND'(\sum_j e_j^*) = 0$$

for $i = 1, \ldots, N$. The symmetric solution where $(k_i^*, e_i^*) = (k_j^*, e_j^*) \equiv (k^*, e^*)$ for all $i, j \in I$ satisfies

$$G'(k^*) + f(\lambda) C_z(e^*, f(\lambda) k^*) = 0, \tag{1}$$

$$C_e(e^*, f(\lambda) k^*) + ND'(Ne^*) = 0 \tag{2}$$

where $f(\lambda) \equiv 1 + (N-1)\lambda$. Similarly, an interior Nash equilibrium $\{\widehat{k}_i, \widehat{e}_i\}$ satisfies

$$G'(\widehat{k}_i) + C_z(\widehat{e}_i, \widehat{k}_i + \lambda \textstyle\sum_{j \neq i} \widehat{k}_j) = 0, \quad C_e(\widehat{e}_i, \widehat{k}_i + \lambda \sum_{j \neq i} \widehat{k}_j) + D'(\sum_j \widehat{e}_j) = 0$$

for all i. The symmetric Nash equilibrium $(\widehat{e}, \widehat{k})$ where $(\widehat{k}_i, \widehat{e}_i) = (\widehat{k}, \widehat{e})$ for all i satisfies

$$G'(\widehat{k}) + C_z(\widehat{e}, f(\lambda) \widehat{k}) = 0, \tag{3}$$

$$C_e(\widehat{e}, f(\lambda) \widehat{k}) + D'(N\widehat{e}) = 0. \tag{4}$$

Under the assumptions on C and D, we can solve conditions (2) and (4) for emissions as a function of investment in the first best allocation and in the Nash equilibrium. Call these functions e^f and e^n. (Superscript f stands for the first best and n for Nash equilibrium. Note that $e^f(k^*) = e^*$ and $e^n(\widehat{k}) = \widehat{e}$.) Similarly, define $k^f(e)$ and $k^n(e)$ to be the investment solutions to conditions (1) and (3) as functions of emissions under the first best solution and the Nash equilibrium, respectively. These functions will prove useful when comparing the optimal and the equilibrium quantities of investments and emissions. They satisfy the following property. (See the appendix for the proofs.)

Lemma 1 *The functions defined above satisfy* $e^n(k) > e^f(k)$ *for all* $k > 0$ *and* $k^n(e) < k^f(e)$ *for all* $e > 0$.

Lemma 2 *The derivatives* $\frac{de^f}{dk}, \frac{de^n}{dk}, \frac{dk^f}{de}, \frac{dk^n}{de}$ *are all negative if* $C_{ez} > 0$, *all positive if* $C_{ez} < 0$, *and are all zero if* $C_{ez} = 0$.

Lemma 3 *The equilibrium investment by each agent is decreasing in the degree of technology spillovers* λ *(i.e.* $\frac{\partial \widehat{k}}{\partial \lambda} < 0$*). The first-best investment by each agent may be decreasing or increasing in technology spillovers. The equilibrium and the first best emissions are nonincreasing (increasing) in* λ *if* $C_{ez} > (<)0$. *The equilibrium emissions are independent of* λ *if* $G'' = 0$.

Lemma 1 states that, given the same investment level, the Nash equilibrium emission is larger than the first best level. Similarly, the equilibrium investment is lower than the first best level given the same emission level. These results hold regardless of whether marginal abatement costs are decreasing in investment. Both the equilibrium and the first best emissions are decreasing (increasing) in investment if the marginal abatement cost is decreasing (increasing) in investment (Lemma 2).

The last part of lemma 3 indicates that $\partial\widehat{k}/\partial\lambda < 0$ while $\partial\widehat{e}/\partial\lambda = 0$ (i.e. the equilibrium emissions are independent of λ) when $G'' = 0$. This can be explained in two ways. First, taking λ as a parameter, we can take the total derivative of $e^n(\widehat{k}(\lambda); \lambda)$ with respect to λ to identify the effect of changes in λ on $\widehat{e}$:

$$\frac{de^n(\widehat{k}(\lambda);\lambda)}{d\lambda} = \frac{\partial e^n(\widehat{k}(\lambda);\lambda)}{\partial \lambda} + \frac{\partial e^n(\widehat{k}(\lambda);\lambda)}{\partial k}\frac{d\widehat{k}(\lambda)}{d\lambda} = -A \cdot C_{ez} - B \cdot C_{ez}\frac{d\widehat{k}(\lambda)}{d\lambda},$$

where A, B are positive.[5] The first term on the right-hand side represents the direct effect of changes in λ on e^n while the second term represents the indirect effect of λ through its effect on k. Both effects depend on the sign of C_{ez}. If $C_{ez} > 0$, then the direct effect implies that, holding k constant, an increase in λ increases the effective capital $z = (1+\lambda(N-1))k$ available to each agent. Then the marginal abatement costs decrease and hence the equilibrium emissions decrease. The indirect effect works in the opposite direction: an increase in λ

[5]Total differentiation of condition (4) with respect to e, k, and λ yields the above expression for $\frac{de^n(\widehat{k}(\lambda);\lambda)}{d\lambda}$ where $A \equiv (N-1)\widehat{k}/(C_{ee} + ND'')$ and $B \equiv f(\lambda)/(C_{ee} + ND'')$.

reduces the equilibrium investment (the first part of lemma 3), which increases the marginal abatement costs given $C_{ez} > 0$ and hence the equilibrium emissions. The directions of the direct and indirect effects are oppositive if $C_{ez} < 0$. Regardless of the sign of C_{ez}, it turns out that these effects cancel each other exactly and hence $\partial\widehat{e}/\partial\lambda = 0$.

The second way to verify $\partial\widehat{e}/\partial\lambda = 0$ given $G'' = 0$ is to look at the conditions for the symmetric Nash equilibrium (3) and (4) given $G'' = 0$:

$$r + C_z(\widehat{e}, \widehat{z}) = 0, \quad C_e(\widehat{e}, \widehat{z}) + D'(N\widehat{e}) = 0,$$

where $r \equiv G' > 0$ and $\widehat{z} \equiv f(\lambda)\widehat{k}$. The solutions to these conditions $\widehat{e}$ and $\widehat{z}$ are independent of λ: That is, the equilibrium quantity of effective capital and emissions are independent of the degree of technology spillovers. Hence, we observe that $\widehat{e}$ and $\widehat{z}$ stay constant as λ changes while each agent's equilibrium investment $\widehat{k} = \frac{\widehat{z}}{1+\lambda(N-1)}$ falls as λ increases.

See section 3.3 for an example where the first-best investment may decrease when the degree of technology spillovers increases.

3.2 Main results

The following proposition is based on the three lemmas and compares the first best solution and the Nash equilibrium outcome of the game where agents choose investment and emissions simultaneously.

Proposition 1 *Let $\{k^*, e^*\}$ be the first best investment and emission of each agent and $\{\widehat{k}, \widehat{e}\}$ be the symmetric Nash equilibrium.*

(i) If $C_{ez} > 0$, then $\widehat{e} > e^*$ and $\widehat{k} < k^*$ for all $\lambda \in [0, 1]$.

(ii) If $C_{ez} = 0$ and $\lambda = 0$, then $\widehat{e} > e^*$ and $\widehat{k} = k^*$. If $C_{ez} = 0$ and $\lambda > 0$, then $\widehat{e} > e^*$ and $\widehat{k} < k^*$.

(iii) If $C_{ez} < 0$ and if the following inequality holds:

$$0 \leq \lambda < \frac{1}{N-1}\left[\frac{C_z(e^n(\widehat{k}), f(\lambda)\widehat{k})}{C_z(e^f(\widehat{k}), f(\lambda)\widehat{k})} - 1\right], \tag{5}$$

then $\widehat{k} > k^*$ and $\widehat{e} > e^*$. If (5) does not hold, then $\widehat{k} \leq k^*$ (but $\widehat{e}$ may or may not exceed e^*). If $C_{ez} > 0$, then $\widehat{e} < e^*$ if and only if

$$C_e(\widehat{e}, f(\lambda)k^n(\widehat{e})) - C_e(\widehat{e}, f(\lambda)k^f(\widehat{e})) > (N-1)D'(N\widehat{e}). \tag{6}$$

The proposition states that the equilibrium emission is larger than the first best level if the marginal abatement cost is nonincreasing in investment ($C_{ez} \geq 0$) or if the spillover effect is small. If the marginal abatement cost is decreasing in investment ($C_{ez} > 0$), then the equilibrium investment is smaller than the first best level regardless of the spillover effect λ. If $C_{ez} = 0$, then the equilibrium investment is the same as the first best level under no spillover while under-investment occurs under spillovers. If the marginal abatement cost is increasing in investment ($C_{ez} < 0$), then over-investment occurs when spillovers and the number of agents are small while under-investment occurs when spillovers or the number of agents are large. Larger marginal abatement costs imply larger ex-post optimal emissions and hence larger damages to each agent. With the marginal abatement costs increasing in investments, each agent's equilibrium investment exceeds the socially optimal level when technology spillovers are small (i.e. when condition 5 holds).

Part (i) has been demonstrated in literature (e.g. Golombek and Hoel 2004) and perhaps not surprising. We explain part (iii) graphically by assuming $C_{ez} < 0$ (Figures 1 and 2). Figure 1 contrasts a representative agent's optimal and equilibrium emission and investment choice. The figure also assumes $\lambda = 0$, and hence the only source of externality is emissions. While the marginal abatement cost of each agent equals the social (aggregate) marginal damages of all agents under the optimal outcome, the equilibrium emission equates the marginal abatement cost and the private marginal damages for each agent (panel b). The assumption $C_{ze} \equiv C_{ez} < 0$ implies that the marginal benefit of investment (i.e. the marginal reduction in abatement cost due to investment) is smaller under smaller emissions (see panel a), and hence the equilibrium investment exceeds the first best level.

Lemma 3 implies that $de^*/d\lambda > 0$ and $d\widehat{e}/d\lambda = 0$ given $C_{ez} < 0$ and $G'' = 0$. These facts open up the possibility that $\widehat{e}$ becomes lower than e^* for λ sufficiently large. Figure 2 illustrates a case where condition (6) holds and hence the equilibrium emission is lower than the first best level. Given $\lambda > 0$, technology spillover is an additional source of externality. The spillovers tend to lower the equilibrium investment relative to the first best level. With λ sufficiently large, the equilibrium investment $\hat{k}$ is lower than the first best level k^* and hence the marginal abatement cost curve given $\hat{k}$ lies to the left of the marginal abatement cost curve given k^*. Therefore, as in Figure 2(b), the equilibrium emission (given by the intersection of the marginal abatement cost given $\hat{k}$ and the private marginal damage) can fall below the first best emission (given by the intersection of the marginal abatement cost given k^* and the social marginal damage).[6]

A remark regarding part (iii) is that condition (5) holds (and hence $\widehat{k} > k^*$) if $\lambda = 0$ or if λ is small. In contrast, condition (6) (and hence $\widehat{e} < e^*$) may not hold even if λ is large. The following example illustrates that the conditions under which (6) may in fact be limited.

[Figure 1]

[Figure 2]

3.3 Example

The following example illustrates the result of Proposition 1:

$$G(k) = k, \quad C(e,z) = f(z) + a(z)(\bar{e} - e) + \frac{b(z)}{2}(\bar{e} - e)^2, \quad D(E) = \frac{d}{2}E^2, \tag{7}$$

where the quantity $\bar{e} > 0$ represents the emission level in the absence of abatement, and $\bar{e} - e$ the abatement level. The linear-quadratic cost specification has been used in many studies including Karp (2006). The function f represents the fixed cost of emission abatement. As explained in the previous section, f may be decreasing or increasing in the effective capital z. We assume f is strictly convex. At an emission level $e \in [0, \bar{e}]$, the marginal abatement cost is given by $a(z) + b(z)(\bar{e} - e)$ and its derivative with respect to investment is $a'(z) + b'(z)(\bar{e} - e)$. For simplicity, assume

$$f(z) = f_0 - f_1 z + \frac{f_2}{2} z^2, \quad a(z) = az, \quad b(z) \equiv b, \tag{8}$$

for all $z \geq 0$ where f_2 and b are positive while f_1 and a may be positive or negative. New technology results in either lower marginal abatement cost, lower fixed cost of abatement, or both. If $a < 0$, then investment results in smaller marginal abatement cost. If $f_1 > 0$ and $a > 0$, then investment results in technologies with lower fixed costs and larger marginal abatement cost. Convexity of C requires $bf_2 - a^2 \geq 0$.

Provided $bf_2 - a^2 = 0$, condition (6) for under-emissions for this example is given by

$$f_1 < \frac{N - \frac{1}{f(\lambda)}}{N - 1}. \tag{9}$$

[6] Though the figure assumes that $G'' = 0$, the argument is also valid when $G'' > 0$.

The necessary and sufficient condition for the equilibrium emission to be interior is $1 < f_1$. The right-hand side of condition (9) decreases monotonically as N increases, and converges to 1. Therefore, condition (9) does not hold if f_1 is large or if N is large.

[Figure 3]

Figure 3 illustrates part (iii) of Proposition 1 using the above example with $N = 2, a = 1, b = 1, d = .75, f_1 = 2, f_2 = 1, \bar{e} = .5$. These parameter values satisfy $C_{ez} < 0$ and $bf_2 - a^2 = 0$, but do not satisfy condition (9). With small technology spillovers, the equilibrium investment level is larger than the optimal level while the equilibrium emissions are always larger than the optimal level.

Figure 4 assumes the same parameter values as Figure 3 except for a smaller value of f_1 such that condition (9) (for $\widehat{e} > e^*$) holds. With large technology spillovers, the equilibrium emissions, as well as the equilibrium investment levels, are smaller than the optimal levels. As Proposition 1 indicates, the equilibrium emission exceeds the optimal level whenever the equilibrium investment is larger than the optimal level.

[Figure 4]

3.4 Investment and emissions under alternative assumptions

We discuss the results under alternative assumptions.

We assumed that the agents choose investment and emissions simultaneously. It might be more natural to assume that the agents choose investment first and then emissions. The result about over-investment under increasing marginal abatement cost holds under the alternative assumption of sequential move.

Though we present our result in the context of transboundary pollution with countries as players, our analysis has an implication to domestic environmental regulation with a regulator and regulated firms as players. A large number of studies have compared regulated firms' incentive for technology innovation and adoption under alternative emission regulation (such as emissions quantity standards, emissions taxes, and emissions trading, see Milliman and Prince 1989, Requate et al. 2003, Jaffe et al. 2003). A number of studies have found that, when the regulator sets emissions standards or emissions taxes after the firms conduct investment, the regulated firms have an incentive to over-invest (relative to the optimal level) under taxes and under-invest under standards (Malik 1991, Kennedy and Laplante 1999, Karp and Zhang 2002, Moledina et al. 2003, Tarui and Polasky 2006). These studies assume that the marginal abatement costs are decreasing in investment. If the marginal abatement costs are increasing investment, then the opposite incentive will work under taxes and standards. Baker et al. (2008) present a thorough summary of the implications of the increasing marginal abatement costs and provide a raking of alternative emission policy instruments under the assumption.

The analysis in this section assumed that the agents are identical. A more realistic model would assume that agents differ in abatement costs and pollution damage functions. With heterogeneity, the equilibrium investment (emission) of some agents may be larger (lower) than the first best level even if the marginal abatement cost is decreasing in investment. This possibility is analogous to the free-rider problem associated with the private provision of public goods: with heterogenous players, those who would benefit most (less) from public goods may contribute more (less) to the supply of public goods.[7]

4 Discussion

This paper studied agents' incentives to reduce emissions of pollutants and develop a new emission abatement technology when technology diffusion across agents may occur and emission reduction is a public good. If the marginal abatement cost of each agent is decreasing in investment, then the Nash equilibrium results in excessive emissions and under-investment in innovation relative to the first-best under any degree of technology spillovers. The equilibrium results in over-investment when spillovers are small enough and if the marginal abatement cost is increasing in investment.

Our study is motivated by a variety of pollution issues where a comprehensive solution needs new technologies, solving the problem is providing a global public good, and the trade-offs we model here are central to policy choices about funding R&D and, in the context of transboundary pollution, about treaty formats regarding coordination on emission control

[7]For example, let $N = 2$ and consider a simple emission game (without investment decisions): $C_i(e_i) = \frac{(1-e_i)^2}{2}$, $D_i(E) = \frac{d_i}{2}E^2$ for $i = 1, 2$. With parameter values $(d_1, d_2) = (0.25, 1)$, the equilibrium emissions are $\widehat{E} \approx 0.89, \widehat{e}_1 \approx 0.78, \widehat{e}_2 \approx 0.11$ while the efficient quantities are $E^* \approx 0.58, e_1^* = e_2^* \approx 0.29$. We have $\widehat{e}_2 < e_2^*$: player 2's equilibrium emission is smaller than the optimal level.

and technology innovation. Our finding implies that the direction to which the incentives for investments and emission reduction are biased depends on the types of technologies involved and the degree of technology spillovers. In particular, the transitions from one pollution abatement technology to another do not necessarily justify subsidizing it even if the emission causes a negative externality. Though the model applies to transboundary pollution and technology spillovers across countries, the implication extends to environmental regulation on industries in a domestic context as well (see section 3.4).

We did not consider several important aspects of investments and emission reduction in international and national contexts such as government-industry interactions (firms' incentive to innovate given costly R&D and/or patenting or licensing opportunities given imperfect appropriability of innovation), heterogeneity among agents, and dynamics (changes in technology, pollution stock, and in the context of transboundary pollution, treaty participation over time). We assumed deterministic innovation.[8] Though some of these issues are discussed in the previous section, further analysis is left for future research.

Appendix

Proof of Lemma 1

We have

$$C_e(e^n(k), f(\lambda)k) + ND'(Ne^n(k)) = C_e(e^n(k), f(\lambda)k) + D'(Ne^n(k)) + (N-1)D'(Ne^n(k)) > 0$$

for all $k > 0$ by condition (4). Because $C_e + ND'$ is increasing in emissions, it follows that $e^n(k) > e^f(k)$ for all $k > 0$.

Similarly, for all $e > 0$ we have

$$G'(k^n(e)) + f(\lambda)C_z(e, f(\lambda)k^n(e)) = G'(k^n(e)) + C_z(e, f(\lambda)k^n(e)) + \lambda(N-1)C_z(e, f(\lambda)k^n(e)) < 0$$

because the sum of the first two terms is zero (condition 3) while the last term is negative. Because $G'(k) + f(\lambda)C_z(e, f(\lambda)k)$ is increasing in investment, the above inequality implies $k^n(e) < k^f(e)$ for all $e > 0$.

■

[8] For the analysis of IEAs with stochastic technological change, see Kolstad (2007).

Proof of Lemma 2

Totally differentiate condition (2) with respect to e^* and k^* to obtain

$$C_{ee}de^* + f(\lambda)C_{ez}dk^* + N^2D''de^* = 0, \quad \text{i.e.} \quad \frac{de^f}{dk} = \frac{-f(\lambda)C_{ez}}{C_{ee} + N^2D''}$$

which is positive if $C_{ez} < 0$ and negative if $C_{ez} > 0$. Similarly, total differentiation of condition (4) yields

$$C_{ee}d\widehat{e} + f(\lambda)C_{ez}dk + ND''d\widehat{e} = 0, \quad \text{i.e.} \quad \frac{de^n}{dk} = \frac{-f(\lambda)C_{ez}}{C_{ee} + ND''}$$

which is positive if $C_{ez} < 0$ and negative if $C_{ez} > 0$.

Totally differentiate condition (1) with respect to e^* and k^* to obtain

$$G''dk + f(\lambda)C_{ze}de + f(\lambda)^2C_{zz}dk = 0, \quad \text{i.e.} \quad \frac{dk^f}{de} = \frac{-f(\lambda)C_{ze}}{G'' + f(\lambda)^2C_{zz}}$$

which is positive if $C_{ez} < 0$ and negative if $C_{ez} > 0$. Similarly, total differentiation of condition (3) yields

$$G''dk + C_{ze}de + f(\lambda)C_{zz}dk = 0, \quad \text{i.e.} \quad \frac{dk^n}{de} = \frac{-C_{ze}}{G'' + f(\lambda)C_{zz}},$$

which is positive if $C_{ez} < 0$ and negative if $C_{ez} > 0$.

■

Proof of Lemma 3

Differentiate the equations (3) and (4) with respect to λ and obtain

$$\begin{pmatrix} G'' + f(\lambda)C_{zz} & C_{ze} \\ f(\lambda)C_{ez} & C_{ee} + ND'' \end{pmatrix} \begin{pmatrix} \frac{\partial\widehat{k}}{\partial\lambda} \\ \frac{\partial\widehat{e}}{\partial\lambda} \end{pmatrix} = \begin{pmatrix} -f'(\lambda)\widehat{k}C_{zz} \\ -f'(\lambda)\widehat{k}C_{ez} \end{pmatrix}.$$

Applying Cramer's Rule, we have

$$\frac{\partial\widehat{e}}{\partial\lambda} = \frac{-f'(\lambda)\widehat{k}G''C_{ez}}{A}, \quad \frac{\partial\widehat{k}}{\partial\lambda} = \frac{-f'(\lambda)\widehat{k}\,[\{C_{ee}C_{zz} - C_{ez}^2\} + NC_{zz}D'']}{A}$$

where

$$A \equiv G''(C_{ee} + ND'') + f(\lambda)\{C_{ee}C_{zz} - C_{ez}^2\} + Nf(\lambda)C_{zz}D'' > 0.$$

Therefore, $\frac{\partial \widehat{e}}{\partial \lambda} \leq (\geq) 0$ if $C_{ez} \geq (\leq) 0$. The equilibrium investment is decreasing in λ ($\frac{\partial \widehat{k}}{\partial \lambda} < 0$) regardless of the sign of C_{ez}.

Similarly, differentiate the equations (1) and (2) with respect to λ and obtain

$$\begin{pmatrix} G'' + f^2 C_{zz} & f C_{ze} \\ f C_{ez} & C_{ee} + N^2 D'' \end{pmatrix} \begin{pmatrix} \frac{\partial k^*}{\partial \lambda} \\ \frac{\partial e^*}{\partial \lambda} \end{pmatrix} = \begin{pmatrix} -f' C_z - f f' k^* C_{zz} \\ -f' k^* C_{ez} \end{pmatrix}.$$

Solving for $\frac{\partial k^*}{\partial \lambda}$ and $\frac{\partial e^*}{\partial \lambda}$, we have

$$\frac{\partial e^*}{\partial \lambda} = \frac{-f' C_{ez}[G'' k^* - f C_z]}{B}, \quad \frac{\partial k^*}{\partial \lambda} = \frac{-f' C_z (C_{ee} + N^2 D'') - f f' k^* \left[\{C_{ee} C_{zz} - C_{ez}^2\} + N^2 C_{zz} D''\right]}{B}$$

where

$$B \equiv G''(C_{ee} + N^2 D'') + f^2 \{C_{ee} C_{zz} - C_{ez}^2\} + f^2 N^2 C_{zz} D'' > 0.$$

Therefore, $\frac{\partial e^*}{\partial \lambda} < (>) 0$ if $C_{ez} > (<) 0$. The sign of $\frac{\partial k^*}{\partial \lambda}$ is indeterminate. ■

Proof of Proposition 1

To show (i), suppose $C_{ez} > 0$. As in the proof of lemma 3, the first best investment k^* satisfies

$$F^*(k^*) \equiv G'(k^*) + f(\lambda) C_z(e^f(k^*), f(\lambda) k^*) = 0.$$

Similarly, the equilibrium investment $\widehat{k}$ satisfies

$$F(\widehat{k}) \equiv G'(\widehat{k}) + C_z(e^n(\widehat{k}), f(\lambda)\widehat{k}) = 0.$$

Note that $\frac{de^f}{dk} < 0$ and $\frac{de^n}{dk} < 0$ by lemma 2 and $C_{ez} > 0$. For any $k \geq 0$ we have

$$F^*(k) - F(k) = f(\lambda) C_z(e^f(k), f(\lambda)k) - C_z(e^n(k), f(\lambda)k)$$

$$\leq C_z(e^f(k), f(\lambda)k) - C_z(e^n(k), f(\lambda)k)$$

where the last inequality follows from $C_z < 0$ and $f(\lambda) \geq 1$ for all $\lambda \in [0, 1]$. Because $C_{ze} > 0$ by assumption and $e^f(k) < e^n(k)$ by lemma 1, we have $C_z(e^f(k), f(\lambda)k) - C_z(e^n(k), f(\lambda)k) < 0$. Hence, $\widehat{k}$ (that satisfies $F(\widehat{k}) = 0$) must be smaller than k^* (that satisfies $F^*(k^*) = 0$) regardless of the value of λ. Finally, $\widehat{k} < k^*$ implies $\widehat{e} = e^n(\widehat{k}) > e^n(k^*) > e^f(k^*) = e^*$.

To show (ii), suppose $C_{ez} = 0$. Then conditions (1) and (2) are equivalent to

$$G'(k^*) + f(\lambda) \phi_k(f(\lambda) k^*) = 0, \tag{10}$$

$$\phi_e(e^*) + ND'(Ne^*) = 0$$

where $\phi_k(z) \equiv C_z(e,z)$ for all e,z and $\phi_e(e) \equiv C_e(e,z)$ for all e,z. These two conditions determine the first best invest and emission independently. Similarly, conditions (3) and (4) for the Nash equilibrium are equivalent to

$$G'(\widehat{k}) + \phi_k(f(\lambda)\widehat{k}) = 0, \tag{11}$$

$$\phi_e(\widehat{e}) + D'(N\widehat{e}) = 0.$$

Lemma 1 implies $\widehat{e} > e^*$ for any λ. If $\lambda = 0$, then conditions (10) and (11) are identical and hence $\widehat{k} = k^*$. If $\lambda > 0$, then

$$G'(k)+\phi_k(f(\lambda)k) = G'(k)+f(\lambda)\phi_k(f(\lambda)k)-(f(\lambda)-1)\phi_k(f(\lambda)k) > G'(k)+f(\lambda)\phi_k(f(\lambda)k)$$

for all k because $\phi_k < 0$. If follows from $G'' + \phi_k' > 0$ that $\widehat{k} < k^*$.

To show (iii), suppose $C_{ez} < 0$. If $\lambda = 0$, then

$$F^*(k) - F(k) = C_z(e^f(k), k) - C_z(e^n(k), k)$$

where $e^f(k) < e^n(k)$ for all k by lemma 1. Because $C_{ze} < 0$, we have

$$C_z(e^f(k), k) > C_z(e^n(k), k)$$

for all k. Hence, $F^*(k) - F(k) > 0$ for all k. This implies that $\widehat{k} > k^*$. Emissions satisfy $\widehat{e} = e^n(\widehat{k}) > e^f(\widehat{k}) > e^f(k^*) = e^*$ where the last inequality follows from lemma 2 and the assumption $C_{ez} < 0$.

For $\lambda > 0$, we have

$$F^{*\prime}(k) = G'' + f(\lambda)C_{ze}\frac{de^f}{dk} + (f(\lambda))^2 C_{zz} = G'' + \frac{(f(\lambda))^2[C_{ee}C_{zz} - C_{ze}^2 + N^2 C_{zz}D'']}{C_{ee} + N^2 D''} > 0,$$

for all $k > 0$. Hence, $\widehat{k} > k^*$ if and only if $F^*(\widehat{k}) > 0$. Because $F(\widehat{k}) = 0$, $F^*(\widehat{k}) = F^*(\widehat{k}) - F(\widehat{k}) > 0$ holds if and only if

$$f(\lambda)C_z(e^f(\widehat{k}), f(\lambda)\widehat{k}) - C_z(e^n(\widehat{k}), f(\lambda)\widehat{k}) > 0.$$

Given $C_z < 0$ and $f(\lambda) = 1 + (N-1)\lambda$, this inequality is equivalent to

$$(N-1)\lambda < \frac{C_z(e^n(\widehat{k}), f(\lambda)\widehat{k})}{C_z(e^f(\widehat{k}), f(\lambda)\widehat{k})} - 1. \tag{12}$$

Inequality $\widehat{k} > k^*$ also implies $\widehat{e} = e^n(\widehat{k}) > e^f(\widehat{k}) > e^f(k^*) = e^*$.

If (12) does not hold, then we have $\widehat{k} \leq k^*$ but $\widehat{e}$ may or may not exceed e^*. In what follows we describe the conditions under which $\widehat{e} < e^*$ occurs. The first best emission e^* and the equilibrium emission $\widehat{e}$ satisfy

$$H^*(e^*) \equiv C_e(e^*, f(\lambda)k^*) + ND'(Ne^*) = 0,$$

$$\widehat{H}(\widehat{e}) = C_e(\widehat{e}, f(\lambda)\widehat{k}) + D'(N\widehat{e}) = 0.$$

It follows from $C_{ee}C_{zz} - C_{ez}^2 \geq 0$ that

$$H^{*\prime}(e) \equiv C_{ee} + f(\lambda)C_{ez}\frac{dk^f}{de} + N^2D'' = \frac{C_{ee}G'' + (f(\lambda))^2[C_{ee}C_{zz} - C_{ze}^2]}{G'' + C_{zz}f(\lambda)^2} + N^2D'' > 0.$$

Thus

$$\widehat{e} < e^* \quad \Leftrightarrow \quad H^*(\widehat{e}) < 0$$

$$\Leftrightarrow \quad H^*(\widehat{e}) - \widehat{H}(\widehat{e}) = C_e(\widehat{e}, f(\lambda)k^f(\widehat{e})) - C_e(\widehat{e}, f(\lambda)k^n(\widehat{e})) + (N-1)D'(N\widehat{e}) < 0$$

$$\Leftrightarrow C_e(\widehat{e}, f(\lambda)k^n(\widehat{e})) - C_e(\widehat{e}, f(\lambda)k^f(\widehat{e})) > (N-1)D'(N\widehat{e}).$$

(Because $k^f(\widehat{e}) > k^n(\widehat{e})$, the left-hand side of the last inequality is nonpositive if $C_{ez} \geq 0$. Therefore, the above inequality holds only if $C_{ez} < 0$.) ∎

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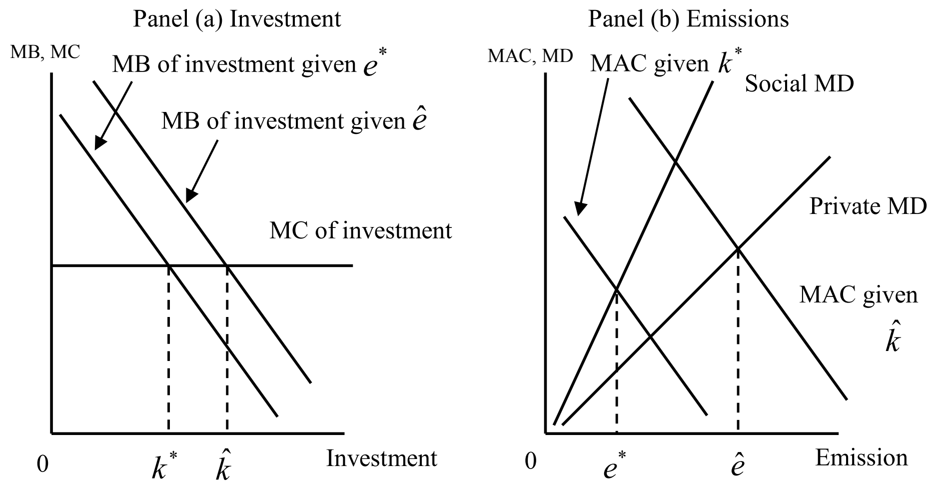
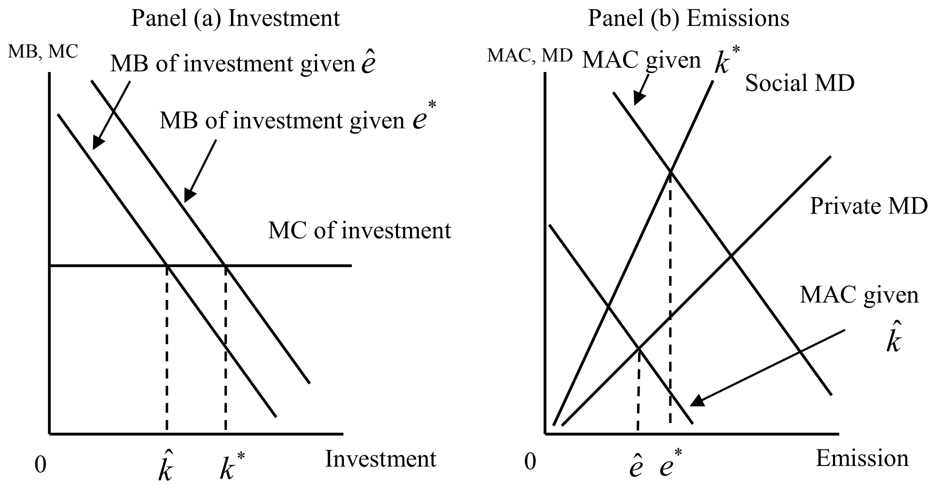
Table 1: Equilibrium outcome of simultaneous-move games

Technology spillovers	Marginal abatement costs			
	Decreasing in R&D		Increasing in R&D	
	Emissions	Investment	Emissions	Investment
Small	Too large	Too small	Too large	Too large
Large	Too large	Too small	?	Too small



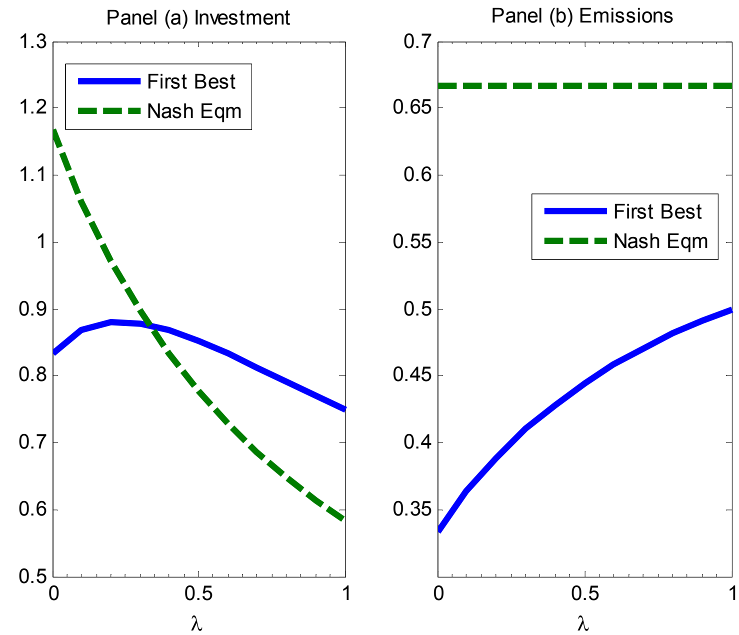
MB of investment is the negative of the partial derivative of abatement cost with respect to investment. MC of investment is the derivative of investment cost. MAC is the negative of the partial derivative of abatement codst with respect to emissions. Private and social MD refer to the marginal damage at a country level and at the aggregate, global level.

Figure 1: The equilibrium and the first best when $C_{ez} < 0$ and $\lambda = 0$.



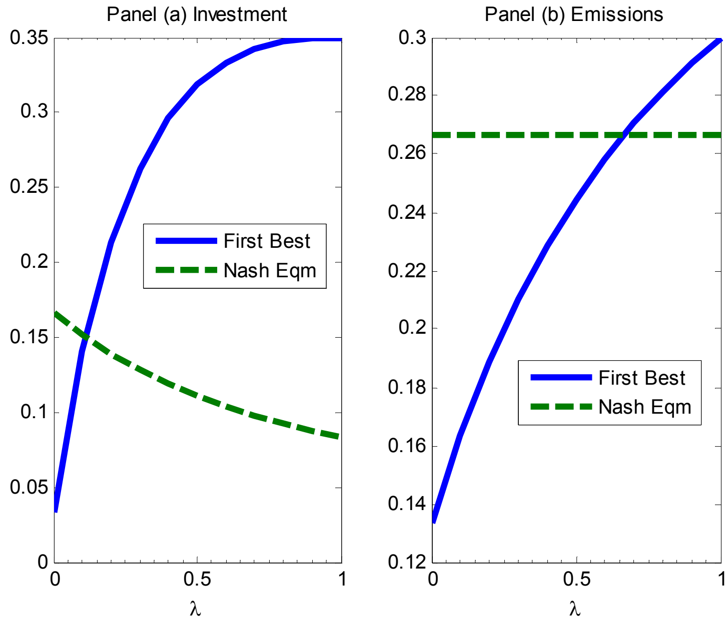
MB of investment is the negative of the partial derivative of abatement cost with respect to investment. MC of investment is the derivative of investment cost. MAC is the negative of the partial derivative of abatement codst with respect to emissions. Private and social MD refer to the marginal damage at a country level and at the aggregate, global level.

Figure 2: The equilibrium and the first best when $C_{ez} < 0$ and a large λ.



The figure is based on a linear quadratic example (equations 7, 8) with N=2, a = 1, b = 1, d = .75, $f_1 = 2$, $f_2 = 1$, $\bar{e} = .5$. In the two panels, the horizontal axes measure the degree of spillovers (0: no spillovers, 1: highest degree of spillovers).

Figure 3: The equilibrium and the first best when $C_{ez} < 0$.



The figure is based on a linear quadratic example (equations 7, 8) with the same parameter values as for Figure 3 except $f_1 = 1.4$ (lower than in Figure 3). In the two panels, the horizontal axes measure the degree of spillovers (0: no spillovers, 1: highest degree of spillovers).

Figure 4: The equilibrium and the first best when $C_{ez} < 0$ (2).