Technology Choice and Environmental Regulation under Asymmetric Information*

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April 24, 2010

Abstract

We focus on the incentives of a regulated firm to invest in a cleaner technology under abatement targets and emission taxation. We assume asymmetric information, in that the regulated firm can be good or bad in employing the new technology. Environmental policy is set either before the firm invests (commitment) or after (time consistency). With abatement targets, commitment usually yields higher welfare than time consistency, because it gives more incentives to invest. With taxation, time consistency usually yields higher welfare, because it gives more incentives to invest. Given investment, targets yield higher welfare according to a modified Weitzman rule with reverse probability weighting. Otherwise, targets yield higher welfare with commitment, because they give more incentives to invest. The welfare comparison under time consistency is ambiguous.

Keywords: asymmetric information, commitment, time consistency, environmental policy

JEL classification: D62, D82, Q28

Work in Progress

*We thank Matti Liski and Marko Terviö for valuable comments.

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1 Introduction

Innovation is a crucial variable to be considered in the design of environmental policy. Since Downing and White [5] and Milliman and Prince [13], an attempt has been made in the literature to compare the relative merits of different environmental policy instruments in terms of their dynamic efficiency properties.[1] Another strand of the literature has focused on the issue of whether the regulator should set environmental policy dimensions before or after investment has actually taken place. In the first case we talk about *commitment*, while, in the second case, we are dealing with *time consistency*.[2]

From its inception by Kydland and Prescott [10] and Fischer [6], the literature has almost unanimously found that with perfect information, commitment is always at least as good as time consistency. Recent environmental policy papers, such as Amacher and Malik [1], Petrakis and Xepapadeas [16], Arguedas and Hamoudi [4] and Requate [18], concluded that time consistency can improve upon commitment in environmental policy.

Amacher and Malik [1] study the case where the regulator sets the emission tax rate either before (commitment) or after (time consistency) the firm has chosen its abatement technology. Amacher and Malik [2] show that unlike emission taxation, an emission standard always implements the first best with commitment.[3] Our paper builds on Amacher and Malik [1] to include asymmetric information. We will find that commitment does not always implement the first best with an emission standard, and time consistency can yield higher welfare in this case as well.

In Petrakis and Xepapadeas' [16] time consistency scenario, the firms first invest in pollution abatement. Then the government sets an emission tax rate. With commitment, the following order of the actions is reversed. Finally, in both scenarios, the firms set their output levels in an imperfectly competitive market. In Arguedas and

[1] See also the surveys in Jaffe et al. [9] and Requate [17].

[2] Downing and White [5] analyze time-consistent policy under the name of "ratcheting" for a single firm in a perfect-information setting.

[3] Mohr [14] shows (like Amacher and Malik [2]) that a time-consistent standard does not yield the first best with perfect information, and offers several suggestion to overcome this problem.

Hamoudi's [4] model, the firm can invest in a technology that reduces the damaging impact of its emissions on the environment. The regulator can inspect the firm and impose a fine if emissions exceed the standard. With time consistency, the firm first invests in technology and then the regulator sets the the standard and the probability of inspection. With commitment, the following order is reversed. Finally, in both scenarios, the firm sets its emission level and is potentially subjected to inspection and a fine. In Requate's [18] model, there is a single firm that can invest in R&D effort to make it more likely that it will find a new technology. If it does, it can sell the technology to the polluting industry. Requate [18] discusses several scenarios for the timing of environmental policy. None of the above papers, however, deals with asymmetric information.

In this paper we analyze the welfare effects of commitment and time consistency for the regulation of a polluting firm that can invest in a cleaner technology. A crucial assumption is the presence of adverse selection. More specifically, we assume that when the firm invests, it can be more or less efficient in employing the new technology, while the old (dirty) technology does not generate any asymmetric information.

One of the first papers dealing with innovation and standard setting under asymmetric information is Yao [23]. The author examines the case where asymmetric information involves firms' innovation capacity. The game consists of two periods and involves a single player (the "industry"). In period one, the regulator sets the period-one emission standard. Then industry chooses a research investment level. This is not observable by the regulator, and neither is the industry's innovation capability. Industry research is either a failure or a success, so that its cost of meeting the standard is either high or low. The game is repeated in period two.

In Yao's [23] paper the regulatory scenario is a mix of commitment and time consistency. There is commitment in the sense that the regulator can commit to the period-i standard in period i, regardless of the outcome of R&D. There is time consistency in the sense that the regulator cannot commit to the period 2 standard in period 1. As a result, the industry underinvests in period-1 R&D effort in an attempt to reduce the regulator's confidence in its ability and to obtain a more lenient standard in period 2.

The regulator partially counteracts this effect by setting a stricter standard in period 1.

Malik [12] compares commitment and time consistency for standard setting for a single firm in a two-period model where the period-2 damage function is revealed in period 2. Under commitment (or precommitment, or permanent regulation, as Malik [12] calls it), the regulator sets the standard for both periods at a time when only period-one damage is known. The firm then invests in abatement capital and complies with the period-one standard. Subsequently, period-two damage is revealed and the firm complies to the period-two standard. With time consistency (or discretion, or interim regulation, as Malik [12] calls it), the regulator only sets the period-one standard in period one. The firm then invests in abatement capital and complies with the period-one standard. Now, the regulator sets the period-two standard after period-two damage is revealed. The advantage of time consistency is then that the regulator has perfect information when she sets the standards. The disadvantage is that the firm will underinvest in abatement capital in period 1 in order to obtain a more lenient period-2 standard. Malik [12] also takes the regulator's enforcement cost into account.

Tarui and Polasky [19] study a simplified version of Malik's [12] game with only a single period and without costly enforcement. However, they analyze taxes as well as standards. With commitment (or rules, as Tarui and Polasky [19] call it), the regulator first sets the tax rate or the standard. Then the firm invests in abatement capital. Uncertainty about environmental damage is resolved, and finally the firm makes its abatement decision. With time consistency (or discretion, as Tarui and Polasky [19] call it), on the other hand, the regulator sets her policy after the firm has invested and damage has been revealed. Commitment would result in the first best if there were no uncertainty about damages, because the firm has a continuous investment decision. With time consistency, the result is again that the firm underinvests with standards and overinvests with taxes. Interestingly, when abatement costs and damage are quadratic, taxes are welfare-superior to standards.

Finally, Moledina et al. [15] compare taxes and tradable permits with grandfathering in a two-firm industry. The regulator does not know the firms' abatement cost and does not take into account that the firms will try to manipulate her beliefs and policy. In a two- as well as in a T-period model (where T may be infinite), Moledina et al. [15] show that firms will underabate under taxation in order to obtain a lower tax rate. The result for tradable permits is less clearcut. On the one hand, both firms benefit from a high permit price, because this will prompt the regulator to issue more permits. On the other hand, the permit buyer (seller) prefers a low (high) permit price.

In our paper, the game structure is close to the one in Tarui and Polasky [19], but asymmetric information is about abatement costs, as in Moledina et al. [15]. We analyze the instruments of environmental taxation and abatement targets for a single firm. Unlike Moledina et al. [15], we assume the regulator realizes that the firm may try to manipulate her beliefs and policy.

Asymmetric information is introduced in that the regulated firm can be good or bad in employing the good technology, if it invests. We focus on realistic contracts, not involving lump sum transfer. We find that with abatement targets, commitment usually yields higher welfare than time consistency, because it gives more incentives to invest. With taxation, time consistency usually yields higher welfare, because it gives more incentives to invest. Given investment, targets yield higher welfare according to a modified Weitzman rule with reverse probability weighting. Otherwise, targets yield higher welfare with commitment, because they give more incentives to invest. The welfare comparison under time consistency is ambiguous.

The paper is organized as follows: Section 2 shows the main structure of the model. In Section we compare commitment and time consistency with abatement targets. In Section 4 we do the same for emission taxation. Section 6 concludes.

2 The model

A regulated firm is currently using technology 0 which is relatively dirty, but it can switch to the cleaner technology θ. The new technology has lower marginal abatement costs,[4] but involves a fixed investment costs. We focus on specific functional forms,

[4] Technological change does not necessarily lead to lower marginal abatement costs for all levels of abatement. Indeed, marginal abatement costs could increase for high abatement levels (Baker et al., 2008).

assuming:

$$C_0(a) = \frac{b}{2}a^2 \tag{1}$$
$$C_\theta(a) = F + \frac{\theta b}{2}a^2 \tag{2}$$

where $F, b > 0$ and $0 < \theta < 1$.

The cost parameter θ can take two values:

- high ($\theta = h$) with probability $1 - v$, implying that the firm is not good in using the new technology
- low ($\theta = l$) with probability v, implying that the firm is efficient in using the new technology.

Of course, $l < h$. The marginal abatement cost curves are given in Figure 1 as MAC_0 for the current technology and MAC_l (MAC_h) for the new technology with low (high) cost.

We assume specific functional forms also for the damage cost functions:

$$D(a) = \frac{d}{2}(e - a)^2$$

where e is (exogenous) business as usual emissions. The marginal environmental damage curve is given in Figure 1 as MED.

The environmental regulator chooses the environmental standard in order to minimize social costs from production, given by:

$$SC_i = C_i(a) + D(a) \tag{3}$$

with $i = 0, h, l$. Social costs for the current technology are:

$$SC_0 = \frac{ba^2}{2} + \frac{d(e-a)^2}{2} \tag{4}$$

With the current technology in place, the socially optimal abatement level is:

$$a_0 = \frac{de}{b+d} \tag{5}$$

Lowest possible social costs under the current technology are therefore:

$$SC_0(a_0) = \frac{bde^2}{2(b+d)} \tag{6}$$

In Figure 1, social cost under the current technology are given by the area OBe.

Social costs with the new technology are:

$$SC_\theta = F + \frac{\theta b a^2}{2} + \frac{d\,(e-a)^2}{2}$$

and the socially optimal abatement level is:

$$a_\theta = \frac{de}{b\theta + d} > a_0 \tag{7}$$

Lowest possible social costs with the new technology are then:

$$SC_\theta(a_\theta) = F + \frac{b\theta de^2}{2(b\theta + d)} \tag{8}$$

In Figure 1, variable social cost with the new technology is given by the area OYe for a high-cost and OZe for a low-cost firm.

We will assume that social cost is lower with the new technology: $SC_0(a_0) > SC_\theta(a_\theta)$ for $\theta = h, l$. From (6) and (8), this implies:

$$F < F_\theta \equiv \frac{bd^2e^2}{2} \frac{1-\theta}{(b+d)\,(bh+d)}$$

It is easily seen that $F_h < F_l$. In Figure 1, F_h is given by the area OBY and F_l by OBZ. Our assumption that social cost is lower with the new technology thus implies:

$$F < F_h \equiv \frac{bd^2e^2}{2} \frac{1-h}{(b+d)\,(bh+d)} \tag{9}$$

We will investigate two environmental policy instruments: abatement targets or (environmental) standards and emission taxation, and two policy regimes: commitment and time consistency.

In stage zero of each game, nature draws the cost parameter θ. The value is revealed to the firm, but not to the regulator. All other parameters are common knowledge.

Under commitment, the regulator sets the abatement target or the emission tax rate in stage one. The regulator cannot make the target or the tax rate dependent on the firm's investment decision. Also, she cannot offer the firm a contract combining different abatement levels with different levels of payment to or from the firm. In stage two, the firm chooses a technology. This order is reversed under time consistency.

Finally, in stage three the firm chooses its abatement level. With abatement targets, it simply complies to the target.

It should be clear from the outset that (unlike in the Amacher and Malik [1],[2] models with perfect information) the regulator cannot achieve the first best under any of these scenarios. Given (9) the first best is for each type to invest and for type θ to abate a_θ given by (7). It is clear from Figure 1 that firm l has lower marginal environmental damage in this case and should be charged a lower tax rate. Under commitment however, the regulator has to set the same target or tax rate for both types. When both types invest under time consistency, the regulator cannot tell them apart and will again have to set the same policy for both.

If the regulator could offer the firm a contract, there are many way in which she could achieve the first best under commitment as well as time consistency. Perhaps the simplest contract that achieves this is the following. Let T be the payment from the firm to the regulator. For any $a \geq a_l$ (with the new or the current technology), normalize T to zero. For any a with $a_h \leq a < a_l$ (again regardless of the technology choice), the firm pays T^* with

$$C_l(a_l) - C_l(a_h) < T^* < C_h(a_l) - C_h(a_h)$$

For any a with $0 \leq a < a_l$ and investment in the new technology, the firm pays $\hat{T}$ with $\hat{T} > T^* + C_h(a_h)$. For any a with $0 \leq a < a_l$ without investment in the new technology, the firm pays $\bar{T}$ with $\bar{T} > T^* + C_h(a_h) + F$.

3 Abatement targets

3.1 Commitment

Under commitment, the regulator sets the abatement target before the firm chooses whether to invest or not. The regulator would like to impose a_l on the efficient firm and a_h on the inefficient one (with a_h and a_l given by (7) for $\theta = h, l$ respectively).

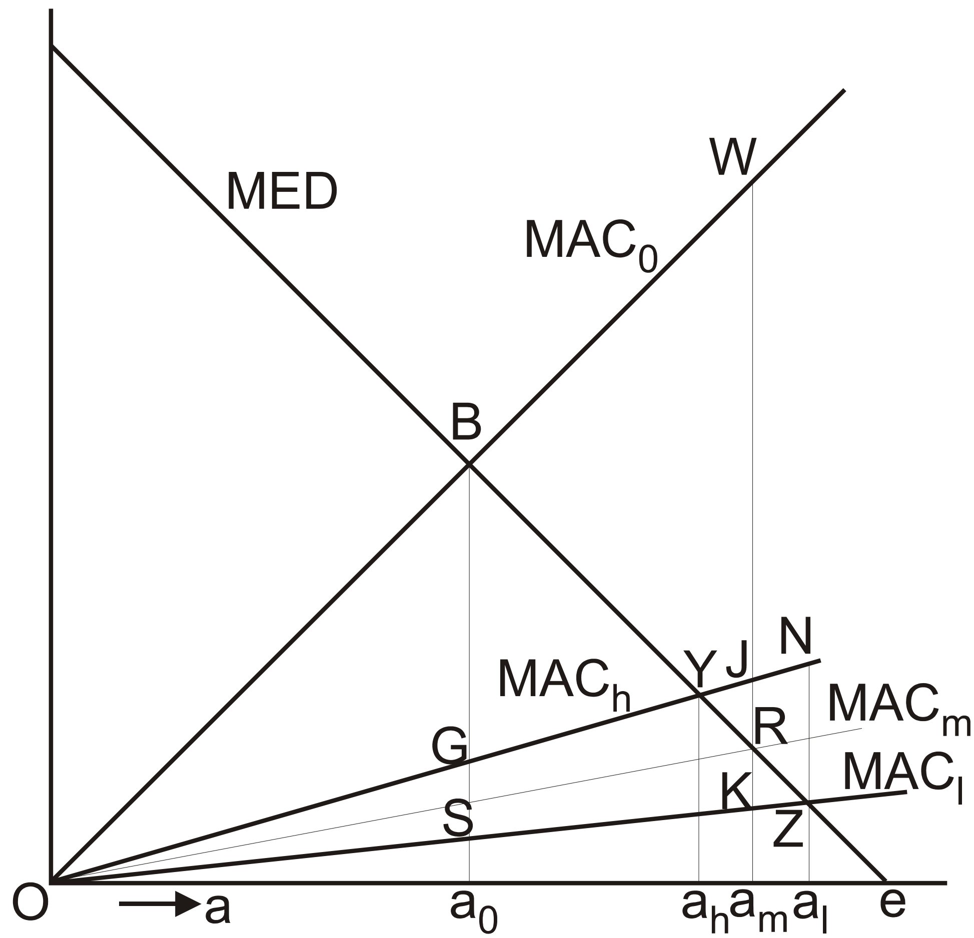

Figure 1: Abatement targets

This is, however, not feasible due to the presence of adverse selection. Since $a_l > a_h$, the efficient firm would claim to be inefficient.

Assuming that both types of firms will invest, the environmental regulator, therefore, minimizes:

$$E(SC) = F + \frac{d}{2}(e-a)^2 + v\frac{lba^2}{2} + (1-v)\,\frac{hba^2}{2}$$

The first order condition is:

$$vbla + (1-v)bha = d\,(e-a) = 0 \tag{10}$$

so that the regulator will set:

$$a_m = \frac{de}{d+\bar{\theta}b} \tag{11}$$

where $\bar{\theta} \equiv lv + h(1-v)$.

Clearly from (7) and (11), $a_h < a_m < a_l$. The expected social costs corresponding to a_m are given by:

$$E\left[SC(a_m)\right] = F + \frac{bde^2}{2}\frac{\bar{\theta}}{d+\bar{\theta}b} \tag{12}$$

In Figure 1, the curve MAC_m represents the LHS of first order condition (10) and $E\left[SC_m(a_m)\right]$ is given by the area ORe.

First of all, we need to check whether investment is, in this case, socially desirable. This happens when

$$E\left[SC(a_m)\right] < SC_0(a_0)$$

or, from (6) and (12), when:

$$F < F_m \equiv \frac{bd^2e^2}{2}\frac{1-\bar{\theta}}{\left(d+b\bar{\theta}\right)(b+d)} \tag{13}$$

Since $\bar{\theta} < h$, it follows from (9) and (13) that $F_h < F_m$. Since we have assumed $F < F_h$, then $F < F_m$ as well. In Figure 1, the expected decrease in social cost, gross of fixed cost, is given by the area OBR. Since F is assumed to be smaller than OBY, it is also smaller than OBR.

Of course, we also need to check whether such pooling abatement level is feasible. In order for it to be feasible, the standard must force both types of firm to invest. This happens when $C_\theta(a_m) < C_0(a_m)$ for each firm type $\theta = h, l$. From (1), (2) and (11), we see that this inequality holds when:

$$F < F_\theta^{co} \equiv \frac{bd^2e^2}{2}\frac{1-\theta}{(d+\theta b)^2} \tag{14}$$

Clearly, we can show that $F_l^{co} > F_h^{co}$. In Figure 1, F_h^{co} is given by OWJ and F_l^{co} by OWK. Furthermore, from (9) and (14):

$$F_h - F_h^{co} = \frac{bd^2e^2}{2}\left(\frac{1-h}{(bh+d)(b+d)} - \frac{1-h}{(bh+d)^2}\right) > 0$$

The inequality follows from $h < 1$. Since we have assumed $F < F_h$, $F < F_h^{co} < F_l^{co}$ holds: Both types of firm will invest if the regulator has set the abatement target at a_m. In Figure 1, OWJ and OWK are larger than OBY.

Thus the equilibrium under commitment is that the regulator sets abatement at a_m, given by (11). Both types of firm invest and expected social cost is given by (12).

3.2 Time consistency

3.2.1 Second stage

Once the firm has chosen whether to invest or not, the regulator has to set the standard.

Suppose the firm did not invest; in this case the regulator will set abatement at a_0 given by (5). When the firm invested in stage one, the standard depends on the regulator's belief about the firm's type. If the regulator believes that both types would have invested, she would set the standard at a_m given by (11). If the regulator believes only the efficient firm would have invested, we know from (7) with $\theta = l$ that she would set:

$$a_l = \frac{de}{d + bl} \tag{15}$$

if the firm invested.

If the regulator believes that firm l would always invest and firm h would invest with probability p, she would set the standard to maximize:

$$E\left[SC\right] = \frac{v}{v + (1-v)p}\frac{lba^2}{2} + \frac{(1-v)p}{v + (1-v)p}\frac{hba^2}{2} + \frac{d}{2}(e-a)^2$$

The first (second) term is the abatement cost of firm l (h) multiplied by the probability that the investing firm is a firm of type l (h). The optimal standard in this case is:

$$\tilde{a} = \frac{\left[v + (1-v)p\right]de}{\left[v + (1-v)p\right]d + vlb + (1-v)phb} \tag{16}$$

It is easily seen that there is no equilibrium in which the inefficient firm would invest, and the efficient firm would not.

We will assume that if the regulator believes neither type of firm would have invested, she would set a_l in the out-of-equilibrium event that the firm did invest.[5]

3.2.2 First stage

In case firm θ anticipates that the regulator will set a_m when it invests, we see from (1), (2), (5) and (11) that it will invest for:

$$F < F_m^\theta \equiv \frac{b}{2}a_0^2 - \frac{\theta b}{2}a_m^2 = \frac{bd^2e^2}{2}\left(\frac{1}{(b+d)^2} - \frac{\theta}{(b\bar{\theta}+d)^2}\right) \tag{17}$$

[5] There is no interval of F for which there is a mixed strategy equilibrium with firm l randomizing and firm h not investing. In this case, the regulator would set a_l after investment. Firm l would only be indifferent between investing and not investing for $F = F_l^l$.

Obviously, $F_m^h < F_m^l$. In Figure 1, F_m^h is given by $OBa_0 - OJa_m = OBG - a_0GJa_m$ and F_m^l by $OBa_0 - OKa_m = OBS - a_0SKa_m$. When $F < F_m^h$, both types will invest.

If firm θ anticipates that the regulator will set a_l when it invests, we see from (1), (2), (5) and (15) that it will invest for:

$$F < F_l^\theta \equiv \frac{b}{2}a_0^2 - \frac{\theta b}{2}a_l^2 = \frac{bd^2e^2}{2}\left(\frac{1}{(b+d)^2} - \frac{\theta}{(bl+d)^2}\right) \tag{18}$$

Again, $F_l^h < F_l^l$.[6] In Figure 1, F_l^h is given by $OBa_0 - ONa_l = OBG - a_0GNa_l$ and F_l^l by $OBa_0 - OZa_l = OBS - a_0SZa_l$. When $F_l^h < F < F_l^l$, only the efficient type will invest.

If firm h expects the regulator to set $\tilde{a}$, it will be indifferent between investing and not investing if:

$$F + \frac{hb\tilde{a}^2}{2} = \frac{ba_0^2}{2} \tag{19}$$

so that (substituting (5)), $\tilde{a}$ has to satisfy:

$$\tilde{a} = \sqrt{\frac{d^2e^2}{h(b+d)^2} - \frac{2F}{hb}} \tag{20}$$

Solving (16) and (20) for p yields:

$$p = \frac{v}{1-v}\frac{de - \tilde{\alpha}(d+lb)}{de - \tilde{\alpha}(d+hb)} \tag{21}$$

We see from (11), (15) and (18) to (21) that $p \to 0$ for $F \to F_l^h$ and $\tilde{a} \to a_l$, while $p \to 1$ for $F \to F_m^h$ and $\tilde{a} \to a_m$. Thus firm h can be made indifferent between investing and not investing for $F \in \left[F_l^h, F_m^h\right]$.

3.2.3 Equilibrium

We know from the analysis above that the critical F values are F_l^h, F_m^h and F_l^l. It follows from (17) and (18) that $F_l^h < F_m^h$. In Figure 1, $OBS - a_0SKa_m$ exceeds $OBS - a_0SZa_l$ by a_mKZa_l. In the Appendix, we show that F_l^l is always larger than F_m^h if the former is positive.

From (9) and (17) we see that:

$$F_m^h = \frac{bd^2e^2}{2}\left(\frac{1}{(b+d)^2} - \frac{h}{(b\bar{\theta}+d)^2}\right) < \frac{bd^2e^2}{2}\frac{1-h}{(b+d)(bh+d)} = F_h$$

[6] We will assume $F_l^h > 0$.

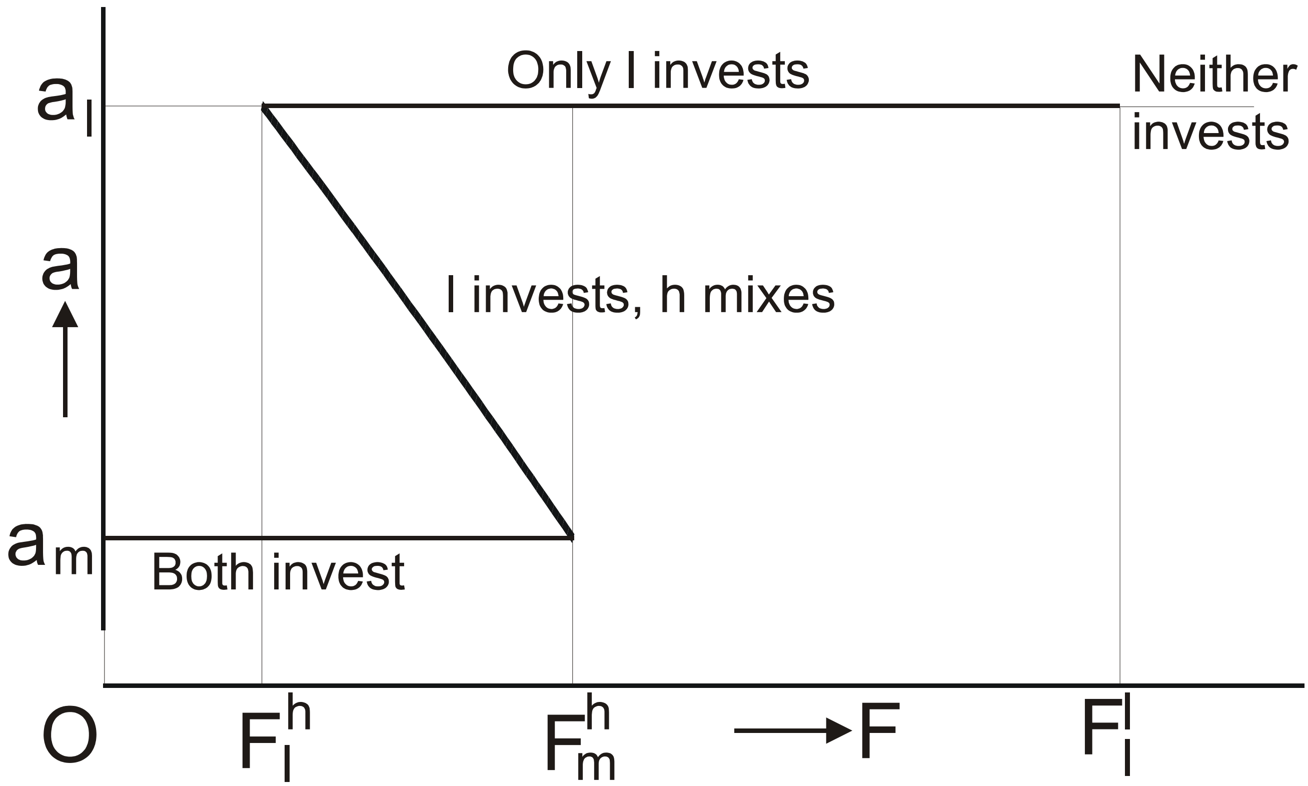

Figure 2: Abatement targets, time consistency: Equilibrium targets and investment decisions.

The inequality follows from $\bar{\theta}, h < 1$. This is also clear from Figure 1, where $OBa_0 - OJa_m$ is smaller than OBY. However, F_l^l and F_m^l can be larger or smaller than F_h.

The equilibria, illustrated in Figure 2, are then as follows:[7]

1. When $F < F_l^h$, both types of firm invest and the regulator sets a_m.

2. When $F_l^h < F < F_m^h$, there are three equilibria. In the first equilibrium, both types of firm invest and the regulator sets a_m. In the second equilibrium, only firm l invests and the regulator sets a_l if the firm has invested. Finally, in the mixed strategy equilibrium, firm l always invests while firm h invests with probability p given by (21). If the firm has invested, the regulator sets $\tilde{a}$ according to (20).

3. When $F_m^h < F < F_l^l$, only firm l invests and the regulator sets a_l if the firm has invested.

[7]Note that in each equilibrium, the regulator sets a_0 if the firm does not invest.

4. When $F > F_l^l$, neither type of firm invests.

3.3 Comparison

We can now compare the equilibrium outcomes under commitment and time consistency. There are four possible equilibria under time consistency. One equilibrium (for $F < F_m^h$) sees both types of firm invest and abate a_m. This is also the only equilibrium under commitment.

For $F_l^h < F < F_l^l$, there is a time consistency equilibrium where firm h does not invest and abates a_0, whereas firm l invests and abates a_l. Expected social cost is:

$$vSC_l(a_l) + (1-v)SC_0(a_0) = v\left(F + \frac{blde^2}{2(bl+d)}\right) + (1-v)\frac{bde^2}{2(b+d)} \tag{22}$$

From (12) and (22), welfare is higher with time consistency if:

$$F < \hat{F} \equiv \frac{bd^2e^2\left((bl+d)(1-h) - bv(h-l)(1-l)\right)}{2(d+bl)\,(b+d)\,(d+bh(1-v)+blv)}$$

If $\hat{F} < F_l^h$, welfare in this range is higher with commitment. If $\hat{F} > F_l^l$, welfare is higher with time consistency. If $F_l^h < \hat{F} < F_l^l$, welfare is higher with time consistency for $F_l^h < F < \hat{F}$, and with commitment for $\hat{F} < F < F_l^l$.

For $F_l^h < F < F_m^h$, there is a mixed strategy equilibrium under time consistency where firm l always invests and firm h invests with probability p. Expected social cost is:

$$E(SC) = vSC_l(\tilde{a}) + (1-v)pSC_h(\tilde{a}) + (1-v)(1-p)SC_0(a_0)$$

To compare this with the commitment equilibrium, let us determine what would happen to expected social cost if p rose marginally from its equilibrium value, but the regulator kept setting the target after investment at α defined by $\partial E(SC)/\partial\alpha = 0$:

$$\begin{aligned}\frac{dE(SC)}{dp} &= (1-v)\left[SC_h(\alpha) - SC_0(a_0)\right] + \frac{\partial E(SC)}{\partial\alpha}\frac{d\alpha}{dp} \\ &= (1-v)\left[SC_h(\alpha) - SC_0(a_0)\right] \leq (1-v)\left[D(\alpha) - D(a_0)\right] < 0\end{aligned}$$

The second equality follows from $\partial E(SC)/\partial\alpha = 0$. The first inequality follows from the fact that $C_h(\alpha) \leq C_0(a_0)$ with equality for $\alpha = \tilde{a}$ (see (19)) and strict inequality for $\alpha < \tilde{a}$ (Note that $d\alpha/dp < 0$ from (16)). The second inequality follows from $\alpha > a_m > a_0$ and $D'(a) < 0$.

Thus, starting from any mixed strategy equilibrium, expected social costs could be reduced if firm h invested with a higher probability. Expected social costs would be lowest for $p = 1$, in which case $\alpha = a_m$. This is exactly the equilibrium with commitment. Thus, the mixed strategy equilibrium under time consistency has higher expected social costs than the commitment equilibrium.

When $F > F_l^l$, in the time consistency equilibrium the firm does not invest and abates a_0. As we have seen in subsection 3.1, welfare in this equilibrium is lower than in the commitment outcome with both types of firm investing and abating a_m.

We can conclude that with targets, commitment generally leads to higher welfare than time consistency. This is because the investment incentive is higher under commitment. In a way, investment is punished under time consistency, because it results in stricter targets. The fact that in the time consistency scenario, the firm's investment decision may reveal something about its type is not very helpful in this setup. In some equilibria, the firm reveals that it is of type h by not investing. However, the regulator would generally prefer firm h to invest.

4 Emission taxation

4.1 Commitment

4.1.1 Preliminaries

Faced with an emission tax rate of t, the firm minimizes its total costs $C_i(a) + t(e - a)$, so that it sets:

$$a_0(t) = \frac{t}{b} \tag{23}$$

with the current technology (1) and

$$a_\theta(t) = \frac{t}{b\theta} \tag{24}$$

with the new technology (2) θ, $\theta = h, l$.

When the firm does not invest at tax rate t, social cost is, from (4) and (23):

$$SC_0(t) = \frac{t^2}{2b} + \frac{d}{2}\left(e - \frac{t}{b}\right)^2 \tag{25}$$

When firm θ invests at tax rate t, social cost is, from (3) and (24):

$$SC_\theta(t) = F + \frac{t^2}{2b\theta} + \frac{d}{2}\left(e - \frac{t}{b\theta}\right)^2 \tag{26}$$

Given a tax rate t, firm θ will invest if:

$$C_0(a_0(t)) + t_m(e - a_0(t)) > C_\theta(a_\theta(t)) + t_m(e - a_\theta(t))$$

or from (1), (2), (23) and (24):

$$F < \bar{F}_\theta(t) \equiv \frac{t^2}{2b}\left(\frac{1}{\theta} - 1\right) \tag{27}$$

4.1.2 Equilibria

We will discuss the commitment equilibria for ascending values of F.

For the lowest values of F, the regulator would like both types of firms to invest, and they will invest. The regulator sets the tax rate to minimize $vSC_l(t) + (1-v)SC_h(t)$, with $SC_\theta(t)$ for $\theta = h, l$ given by (26). The optimal tax rate is:

$$t_m = \frac{bdehl\left[l(1-v) + hv\right]}{d(l^2(1-v) + h^2 v) + bhl\left[l(1-v) + hv\right]} \tag{28}$$

Expected social cost is:

$$E\left[SC(t_m)\right] = F + \frac{de^2\left(bh^2lv + bhl^2(1-v) + dv(1-v)(h-l)^2\right)}{2\left(dl^2(1-v) + bhl^2(1-v) + dh^2v + bh^2lv\right)} \tag{29}$$

By (27), firm θ will invest at a tax rate of t_m if:

$$F < \bar{F}_m^\theta \equiv \frac{t_m^2}{2b}\left(\frac{1}{\theta} - 1\right) \tag{30}$$

with t_m given by (28). $\bar{F}_m^h$ is given by area OKG in Figure 3. $\bar{F}_m^l$, which is larger than $\bar{F}_m^h$, is given by area OKS. As long as $F < \bar{F}_m^h$, both types of firm will invest under a tax rate of t_m. However, it is clear from Figure 3 that $\bar{F}_m^h < F_h$: area OKG is smaller than OBY.

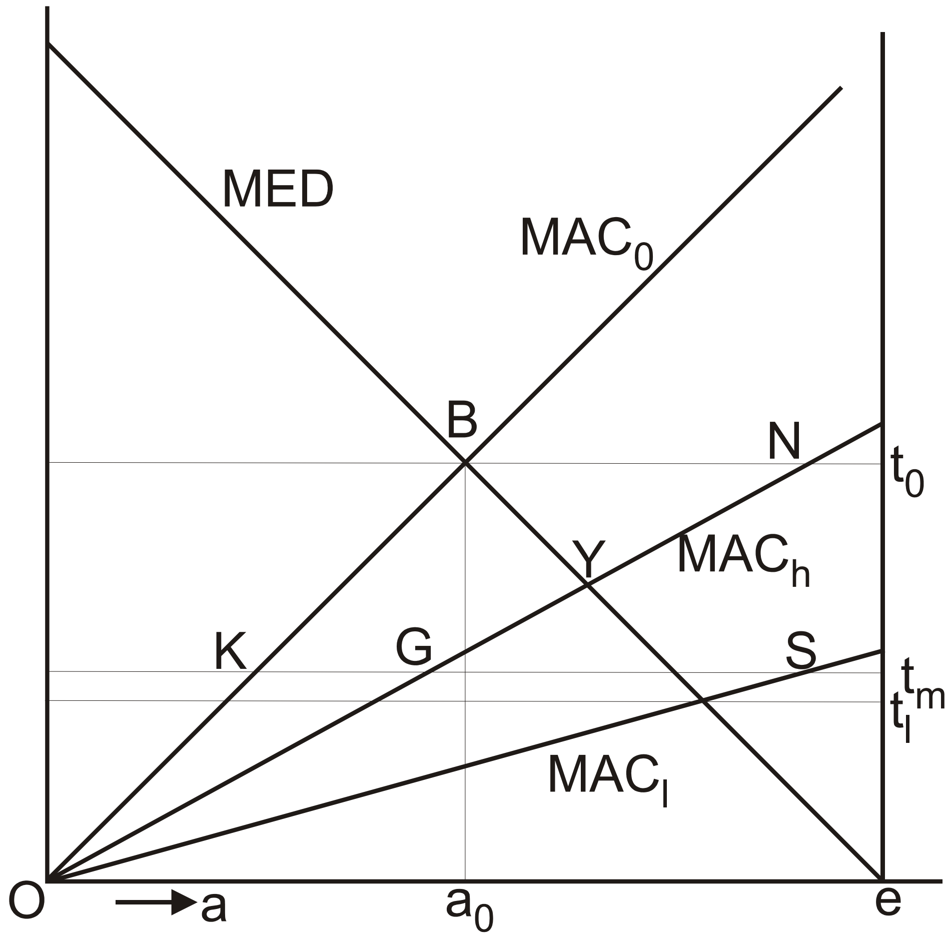

Figure 3: Emission taxation

For F just above $\bar{F}_m^h$, the regulator will set the tax rate such that firm h will just be inclined to invest. The tax rate where firm h is indifferent between investing and not is given by (27) for $\theta = h$, or, solving for t:

$$t = \hat{t}_h \equiv \sqrt{\frac{2bhF}{1-h}}$$

Expected social cost is:

$$E\left[SC\left(\hat{t}_h\right)\right] = F + v\left(\frac{hF}{l(1-h)} + \frac{d}{2}\left[e - \sqrt{\frac{2hF}{bl^2(1-h)}}\right]^2\right) + (1-v)\left(\frac{F}{1-h} + \frac{d}{2}\left[e - \sqrt{\frac{2F}{bh(1-h)}}\right]^2\right) \tag{31}$$

As F rises further, there comes a point where the regulator prefers not to induce firm h to invest, but rather sets the optimal tax rate given that firm h does not invest, but firm l does. Expected social cost would be $vSC_l(t) + (1-v)SC_0(t)$ from (25) and (26) with $\theta = l$. The optimal tax rate is:[8]

$$\hat{t}_m = \frac{bdel\left[l(1-v)+v\right]}{d(l^2(1-v)+v)+bl\left[l(1-v)+v\right]} \tag{32}$$

Expected social cost is then:

$$E\left[SC(\hat{t}_m)\right] = vF + \frac{de^2\left(bl(l(1-v)+v)+dv(1-v)(1-l)^2\right)}{2\left[bl(l(1-v)+v)+d(l^2(1-v)+v)\right]} \tag{33}$$

Setting expected social cost in (31) and (33) equal to each other yields $\bar{F}_h$, the level of F where the regulator is indifferent between setting $\hat{t}_h$ and $\hat{t}_m$.[9]

Firm l will invest at $\hat{t}_m$ as long as F is below $\bar{F}_l \equiv \bar{F}_l(\hat{t}_m)$ from (27). For F just above $\bar{F}_l$, the regulator will set the tax just above the rate that makes firm l indifferent between investing and not investing. From (27) with $\theta = l$, this tax rate is:

$$t = \hat{t}_l \equiv \sqrt{\frac{2blF}{1-l}} \tag{34}$$

Expected social cost is:

$$E\left[SC\left(\hat{t}_l\right)\right] = v\left(F + \frac{F}{1-l} + \frac{d}{2}\left[e - \sqrt{\frac{2F}{bl(1-l)}}\right]^2\right) + (1-v)\left(\frac{lF}{h(1-l)} + \frac{d}{2}\left[e - \sqrt{\frac{2lF}{bh^2(1-l)}}\right]^2\right) \tag{35}$$

For high enough F, the regulator prefers firm l not to invest at $\hat{t}_l$. The level of F where the regulator is indifferent between firm l investing and not investing is defined by $SC_0(\hat{t}_l) = SC_l(\hat{t}_l)$ or, from (25), (26) and (34):[10]

$$F = \bar{F}_0 \equiv \sqrt[4]{2bl(1-l)}\sqrt{\frac{de}{d+2bl+dl}}$$

For $F > \bar{F}_0$, the regulator sets t just below $\hat{t}_l$, to make sure firm l does not invest.

For the next bracket of F, the equilibrium would feature the regulator setting:

$$t_0 = \frac{bde}{b+d} \tag{36}$$

This is the optimal tax rate given that neither type of firm invests. However, in Figure 3, firm h would only refrain from investing at t_0 for fixed cost above OBN. Since we have assumed that fixed cost is less than OBY, this equilibrium cannot occur.

[8] To make sure firm h does not invest at $\hat{t}_m$, we will assume $\hat{t}_m$ is below $\hat{t}_l$ at $\bar{F}_h$. This holds for high enough v.

[9] The explicit expression for $\bar{F}_h$ is available from the corresponding author upon request.

[10] We shall assume that $\bar{F}_0 < F_h$ in (9).

4.2 Time consistency

Let us start the analysis in stage two. If the firm has not invested, the regulator sets the tax rate at t_0 according to (36). If the firm has invested and the regulator believes both types would have invested, she sets the tax rate at t_m according to (28). If the firm has invested and the regulator believes only firm l would have invested, she sets the tax rate at t_l that minimizes $SC_l(t)$ in (26):

$$t_l = \frac{blde}{bl + d}$$

We will assume that if the regulator believes neither type would have invested, she will set the tax rate at t_l in the out-of-equilibrium event of investment.

Now we move to stage one, the firm's investment decision. If the firm expects the government to set the tax rate at t_m after investment, both types of firm will invest. In Figure 3, firm h would gain OBt_0t_mG and firm l would gain OBt_0t_mS from investing. Both exceed the F_h of OBY. If the firm expects t_l after investment, again both types of firm will invest, because obtaining a tax rate of $t_l < t_m$ is even more attractive than a tax rate of t_m.

The only equilibrium is then the path where both types of firms invest and the government sets the tax rate at t_m according to (28).

4.3 Comparison

When $0 < F < \bar{F}_m^h$, commitment and time consistency lead to the same outcome and therefore the same welfare: Both types of firms invest at a tax rate of t_m. Note that this is always the equilibrium with time consistency.

When $\bar{F}_m^h < F < \bar{F}_h$, the regulator sets the tax rate at $\hat{t}_h - \varepsilon$ with commitment, just inducing firm h to invest. Given that both types invest, t_m would be the optimal tax rate. Thus, time consistency leads to higher welfare than commitment.

When $\bar{F}_h < F < \bar{F}_l$, the regulator sets the tax rate at $\hat{t}_m$ with commitment, which is the optimal tax rate given that firm l invests and firm h does not. Note that expected social cost is the same at $\bar{F}_h$, whether the regulator sets $\hat{t}_h$ or $\hat{t}_m$ with commitment. Since at $\bar{F}_h$ with $\hat{t}_h$, welfare is higher with time consistency, the same is true for F just above $\bar{F}_h$. However, the higher F, the lower expected social cost (33) under commitment with $\hat{t}_m$ compared to time consistency (29). Thus for high enough F (just below $\bar{F}_l$), commitment may lead to higher welfare than time consistency.

When $\bar{F}_l < F < \bar{F}_0$, the regulator sets the tax rate at $\hat{t}_l - \varepsilon$ with commitment, just inducing firm l to invest. As with $\bar{F}_h$, expected social cost is the same at $\bar{F}_l$, whether the regulator sets $\hat{t}_m$ or $\hat{t}_l$ with commitment. Thus, welfare may be higher with commitment for low F values in this interval. For F values close to $\bar{F}_0$, however, welfare is higher with time consistency, as we shall see shortly.

When $\bar{F}_0 < F < F_h$, the regulator sets the tax rate at $\hat{t}_l + \varepsilon$ with commitment, just inducing firm l not to invest. However, given that the firm does not invest, the optimal tax rate would be t_0 given by (36). Thus social cost with commitment exceeds OBE in Figure 3. Expected social cost (29) with time consistency is decreasing in the probability v of the firm being low-cost. It is thus highest for $v = 1$: the firm is high-cost with certainty. But even then, social cost with time consistency would only be OYe plus F. Since F is smaller than $F_h = OBY$ by assumption, welfare is higher with time consistency. Since expected social cost is the same at $\bar{F}_0$, whether the regulator sets $\hat{t}_l + \varepsilon$ or $\hat{t}_l - \varepsilon$ with commitment, time consistency also yiels higher welfare for F just below $\bar{F}_0$.

Thus we see that usually welfare is at least as high with time consistency as with commitment. Only for F values around $\bar{F}_l$ might commitment result in higher welfare. The main reason for the better welfare performance of time consistency is that investment is rewarded with a decrease in the tax rate. While the time consistency scenario might allow the regulator to learn something about the firm's type from its investment decision (and this does happen in some time-consistent equilibria with targets, as we have seen in subsection 3.2.3), this does not happen in the equilibrium with taxation.

5 Comparing the instruments

5.1 Investment incentives

Under time consistency, taxation always leads to investment, while targets do not. This is because taxation rewards investment, while targets punish it. The regulator

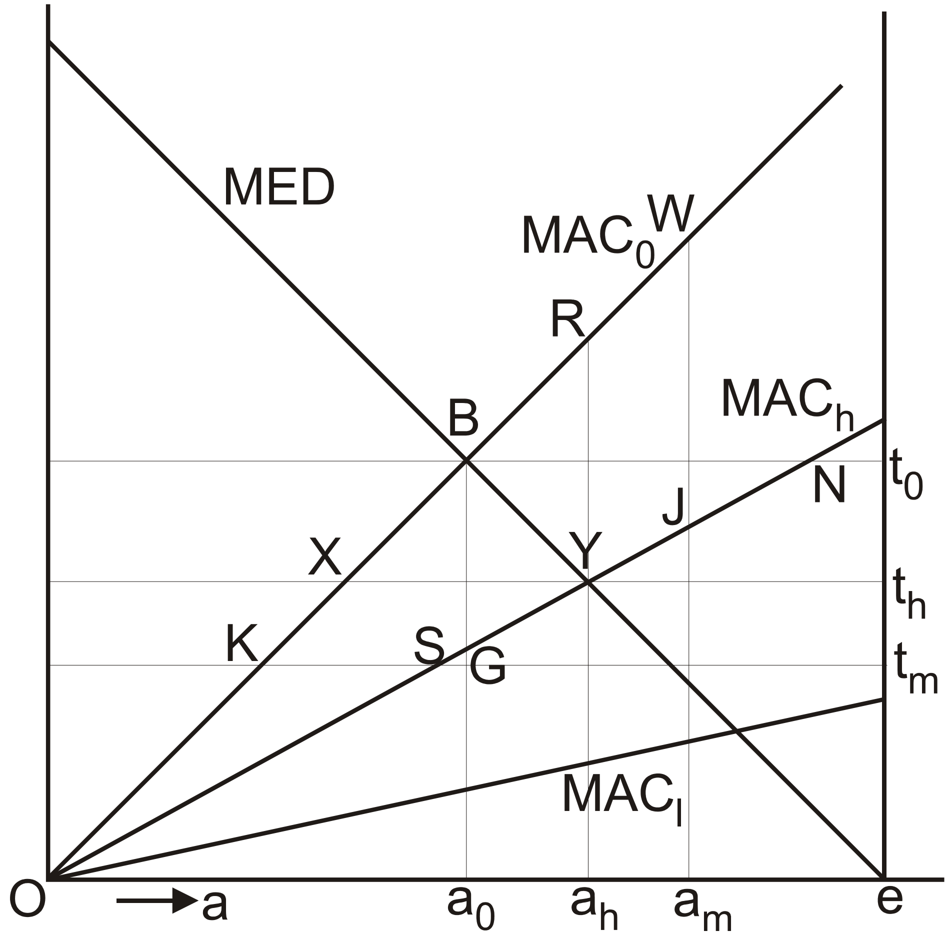

Figure 4: Investment incentives with commitment: targets and taxation compared

responds to the firm's investment by setting a lower tax rate, but a stricter target.

The situation is reversed with commitment: targets always lead to investment, while taxation does not. This can be explained with the aid of Figure 4, where we focus on firm h, because this is the type that is least inclined to invest. Let us start with the case where the regulator knows with certainty that the firm is type h and she expects the firm to invest. With targets, she will then set a_h. The firm's abatement cost without investment is ORa_h whereas with investment it is OYa_h. The firm will thus invest if $F < ORY$. With taxation, the regulator sets t_h. The firm's abatement cost plus tax payment without investment is OXt_he, whereas with investment it is OYt_he. The firm will thus invest if $F < OXY$. We see that the incentive to invest under taxes is smaller than under targets, because $OXY < ORY$.

This finding runs counter to the standard textbook argument that taxes provide a larger investment incentive than targets.[11] The argument there is that with targets, investment only allows for the existing target to be met at lower cost, while taxation gives the option to abate more and to save on the tax bill. The textbook argument assumes that the instruments are set such that they result in the same abatement level pre-investment, for instance a target of a_0 and a tax rate of t_0. Then the firm would invest under targets if $F < OBG$ and under taxes if $F < OBN$, with $OBN > OBG$: the investment incentive is higher with taxes. Comparing the instruments for a given pre-investment level of abatement may make sense if it is assumed that the regulator is myopic, it takes time to change policy, or the firm under consideration is a small firm among many others. However, we are looking at the case of a single firm, with a welfare-maximizing regulator that can set the policy just before the firm makes its invetment decision. In this case, if the regulator knows that the firm is going to invest, she should set the instruments such that they result in optimal abatement post-investment.

Now let us consider the effect of asymmetric information, in which case there is a probability that the firm is not of type h, but of type l instead. Again we look at the case where the regulator expects firm h to invest, which obviously implies that firm l will also invest. With targets, the regulator sets $a_m > a_h$. Following the reasoning above, the firm will invest for $F < OWJ$. Note that $OWJ > ORY$ because $a_m > a_h$. Thus, asymmetric information increases firm h's investment incentive under targets. With taxation, the regulator sets $t_m < t_h$ and the firm will invest for $F < OKS$. We see that $OKS < OXY$ because $t_m < t_h$. Thus asymmetric information decreases firm h's investment incentive under taxes.

We have found that under perfect information, abatement targets give more incentive to invest than taxes. Asymmetric information increases the investment incentive for abatement targets and decreases it for taxes. Thus, asymmetric information makes the investment incentive gap even larger in favour of abatement targets.

[11] E.g. Hanley et al. [7], Figure 5.7, p. 162. The first graphical exposition of this argument appears to be by Downing and White [5], Figure 2, p. 20.

5.2 Welfare

Comparing welfare between the two instruments, there are two aspects to be considered:

1. The welfare comparison given that both types of firm invest, and the regulator sets the optimal policy given that they do.

2. The case where the firm does not always invest, or at least the regulator cannot take for granted that the firm always invests.

For case 1, we obtain a variant of the familiar Weitzman [21] result that the comparison depends on the relative slopes of the marginal abatement cost and the marginal environmental cost curves. We find that expected social cost is higher under taxes if and only if:

$$b\left[l(1-v)+hv\right]<d \tag{37}$$

The result is reminiscent of Weitzman [21] in that the weighted average slope of the MAC curve has to be smaller than the slope of the MEC curve. However, the probability weighting is reversed: the slope of firm l's MAC curve is weighted with the probability that the firm is of type h, and vice versa. This is a new result in the "prices vs. quantities" literature which, following Weitzman [21], has mainly concentrated on additive uncertainty (i.e. about the intercept of the MAC curve). We are analyzing multiplicative uncertainty (i.e. about the slope of the MAC curve). Weitzman ([21], fn. p. 486; [22]) and Malcomson [11] have previously derived expressions for the comparative advantage of prices over quantities in this case. However, the role of reverse probability weighting is not apparent from these expressions nor is it discussed by the authors.[12]

We can explain the reverse probability weighting with the aid of Figure 5. Suppose the regulator is practically certain that the firm is of type h. It would then set the

[12] Watson and Ridker [20] and Hoel and Karp [8] also analyze multiplicative uncertainty. However, they do not offer explicit expressions for the comparative advantage of prices over quantities, focusing instead on simulations (Watson and Ridker [20] on several pollutants in the US and Hoel and Karp [8] on climate change).

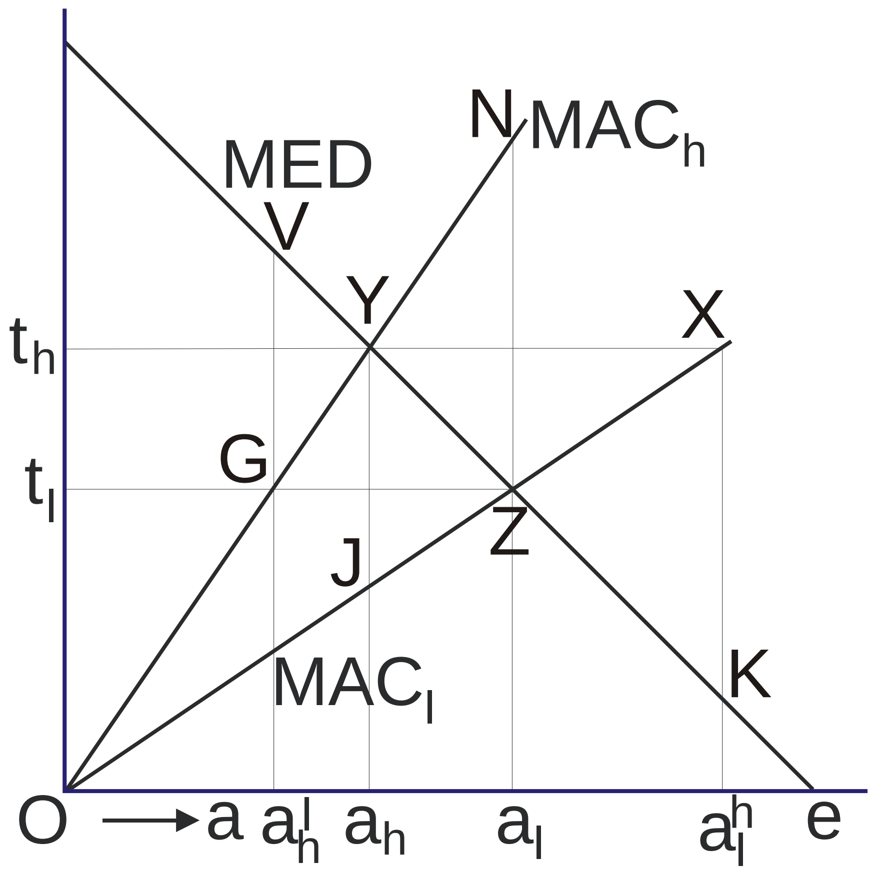

Figure 5: The modified Weitzman rule with reverse probability weighting

abatement target at a_h and the tax rate at t_h. If, against all expectations, the firm is of type l, the welfare loss is JYZ with targets and ZXK with taxation. The welfare loss is larger with taxes, because MAC_l is flatter than MED. This result is similar to Weitzman [21], however the new element is that it is the slope of the MAC curve in the unlikely scenario (that the firm is of type l in this example) that is relevant for the comparison between targets and taxes.[13] In general, the slope of the MAC curve in the less likely scenario receives a larger weight. This explains the reverse probability weighting of the MAC slopes in (37).

In our analysis, inequality (37) always holds, so that standards are better than taxes in Case 1. The inequality always holds, because F_l^h in (18) with $\theta = l$ has to be

[13] If the regulator is practically certain that the firm is of type l, it would set the abatement target at a_l and the tax rate at t_l. If the firm is of type h, the welfare loss is GVY with targets and YFZ with taxation. The welfare loss is larger with targets, because MAC_h is steeper than MED.

positive, as explained in the Appendix. F_l^h is firm h's gain from investing under time consistency when the regulator sets the standard at a_l after investment. In Figure 1, F_l^h is given by the area $OBG - a_0GNa_l$. As the Figure demonstrates, MAC_h has to be quite flat for this area to be positive. Indeed, it has to be flatter than the MED curve.

For case 2, we can compare the instruments under commitment and under time consistency. The comparison under commitment is aided by our comparison of commitment and time consistency for taxation in subsection 4.3. This is because the outcome of standards under commitment and taxes under time consistency is very similar: Both lead to investment by the firm, and the optimal policy given that the firm invests. We know from the above analysis of case 1 that in this case, standards under commitment yield higher welfare than taxes under time consistency. We have seen in subsection 4.3 that with taxation, time consistency generally leads to higher welfare than commitment. Only for F values around $\bar{F}_l$ could commitment lead to higher welfare. We thus find that with commitment, standards generally yield higher welfare than taxes. It is still possible that taxes yield higher welfare for F values around $\bar{F}_l$. The main reason why standards yield higher welfare is that they offer higher investment incentives, as we have seen in subsection 5.1.

With time consistency, the equilibrium under taxation is investment and a tax rate of t_m. The welfare comparison with all three equilibria under targets (firm l invests and h mixes; firm l invests and h does not; firm does not invest) is ambiguous. For instance, for the highest possible F value of F_h, we find from (6), (9) and (29):

$$SC_0(a_0) - E\left[SC(t_m)\right] = \frac{d^2ve^2(h-l)\left[bh(hv+l(1-v)) - d(h-l)(1-v)\right]}{2\left(d+bh\right)\left(dl^2(1-v) + bhl^2(1-v) + dh^2v + bh^2lv\right)}$$

The sign is determined by the expression in square brackets in the numerator. This expression is increasing in v. For $v = 1$, it is always positive: social costs are higher with targets. For low v values, the expression may well be negative, so that social costs are higher with taxation.

Thus, while taxation has the advantage of always resulting in investment, this does not necessarily mean it outperforms targets when the latter do not always lead to investment. The reason is that, as we saw with case 1, taxation results in lower welfare than targets given that the firm invests.

6 Conclusion

The incentives provided for the adoption of cleaner technologies are a crucial variable when dealing with the design of environmental policy. The regulatory framework can be particularly complicated when the involved technology is relatively new, so that the regulator herself might not possess all the relevant information. We model such a situation by assuming that when the firm invests, the environmental authority cannot observe whether the regulated firm is efficient or inefficient in using the adopted technology. We address the performance of environmental standards and emission taxes under two institutional settings, commitment and time consistency. With commitment (time consistency), the regulator sets environmental policy before (after) the firm has made its investment decision.

We find that with abatement targets, welfare is usually higher with commitment. This is because commitment gives more incentive to invest in the new technology. With time consistency, investment is discouraged because it leads to a stricter target. With time consistency, while the firm's investment decision might give the regulator some information about its type, this does not help the regulator much in terms of welfare. Information is only revealed in case the high-cost type does not invest, but in general, the regulator would like the high-cost firm to invest.

With taxation, the welfare comparison is reversed: welfare is usually higher with time consistency. Again, as with targets, the scenario that gives the highest incentive to invest in the new technology generally yields the highest welfare. With taxation, investment is rewarded under time consistency, because it leads the regulator to set a lower tax rate. Whereas there was information revelation under time consistency with targets, no information is revealed with taxation.

Comparing the instruments with each other, we see that under commitment, the investment incentive is higher with abatement targets. When the regulator expects the firm to invest, it will set a strict target (encouraging investment), but a low tax rate (discouraging investment). In the standard textbook analysis, taxes give higher investment incentives than targets. This is because the latter compares the instruments at their pre-investment levels, while we compare them at their post-investment levels. Under time consistency, taxation gives higher investment incentives, because when the firm invests, it is rewarded by a lower tax rate, or punished by a stricter standard.

For the welfare comparison in the case where both instruments lead to investment and policy is optimal given investment, we derive a modified Weitzman [21] rule with reverse probability weighting. Under our assumptions, the marginal abatement cost curve is always flatter than the marginal environmental damage curve, so that targets yield higher welfare. In case investment does not occur or cannot be taken for granted, targets usually yield higher welfare than taxation under commitment. The welfare comparison under time consistency is ambiguous.

7 Appendix

7.1 Proof of $F_l^l > F_m^h$

In this appendix we show that $F_l^l > F_m^h$ if the former is positive. From (17) with $\theta = h$, we see that F_m^h is increasing in $\bar{\theta}$. It is thus highest for $v \to 0$ and $\bar{\theta} \to h$, so that:

$$F_m^h < F^* \equiv \frac{bd^2e^2}{2}\left(\frac{1}{(b+d)^2} - \frac{h}{(bh+d)^2}\right) \tag{38}$$

A necessary condition for $F_m^h > F_l^l$ would be for $F^* > F_l^l$. In addition, since it would be irrelevant for our analysis if we found that $F_m^h > F_l^l$ only when both variables are negative, we would like to see $F_m^h > 0$. A necessary condition for the latter is $F^* > 0$. From (18) with $\theta = l$ and (38), the inequalities $F^* > F_l^l$ and $F^* > 0$ imply respectively:

$$\frac{h}{(bh+d)^2} < \frac{l}{(bl+d)^2}, \qquad \frac{h}{(bh+d)^2} < \frac{1}{(b+d)^2} \tag{39}$$

Both inequalities can be satisfied simultaneously only if the function

$$f(\phi) = \frac{\phi}{(b\phi+d)^2} \tag{40}$$

has an interior minimum in the interval $\phi \in [l, 1]$. Taking the first derivative of $f(\phi)$, we find:

$$f'(\phi) = \frac{d - b\phi}{(b\phi+d)^3}$$

Thus $f(\phi)$ only has one stationary point globally, at $\phi = \bar{\phi} \equiv d/b$. Taking the second derivative at this point, we find:

$$f''(\bar{\phi}) = \frac{-b}{(b\bar{\phi} + d)^3} < 0$$

Thus the stationary point of $f(\phi)$ is a maximum, which implies that the two inequalities in (39) cannot be satisfied simultaneously and F_l^l must exceed F_m^h if the former is positive.

7.2 Comparing instruments when both types of firm invest

A necessary condition for (37) not to hold is that $bh > d$. In subsection 7.1 we saw that the function $f(\phi)$ as defined in (40) has a unique global maximum at $\phi = \bar{\phi} \equiv d/b$. If $bh > d$, then $\bar{\phi} < h$. As a result, $f(h) > f(1)$, so that from (18):

$$F_l^h = \frac{bd^2e^2}{2}\left(\frac{1}{(b+d)^2} - \frac{h}{(bl+d)^2}\right) < \frac{bd^2e^2}{2}\left[f(1) - f(h)\right] < 0$$

This contradicts our assumption that $F_l^h > 0$.

References

[1] Amacher, Gregory S. and Arun S. Malik (2001), "Pollution taxes when firms choose technologies", *Southern Economic Journal* 68: 891-906.

[2] Amacher, Gregory S. and Arun S. Malik (2001), "Price and quantity regulation with discrete technologies", Department of Economics working paper, George Washington University.

[3] Baker, Erin, Leon Clarke and Ekundayo Shittu (2008), "Technical change and the marginal cost of abatement", *Energy Economics* 30: 2799-2816.

[4] Arguedas, Carmen and Hamid Hamoudi (2004), "Controlling pollution with relaxed regulations", *Journal of Regulatory Economics* 26: 85-104.

[5] Downing, Paul B. and Lawrence J. White (1986), "Innovation in pollution control", *Journal of Environmental Economics and Management* 13: 18-29.

[6] Fischer, Stanley (1980), "Dynamic inconsistency, cooperation and the benevolent dissembling government", *Journal of Economic Dynamics and Control* 2: 93-107.

[7] Hanley, Nick, Jason F. Shogren and Ben While (2007), *Environmental Economics in Theory and Practice*, second edition, Palgrave Macmillan, Basingstoke/New York.

[8] Hoel, Michael and Larry Karp (2001), "Taxes and quotas for a stock pollutant with multiplicative uncertainty", *Journal of Public Economics* 82: 91-114.

[9] Jaffe, A.B., Newell, R.G., Stavins, R.N. (2003), "Technological change and the environment", in K.-G. Maler and J.R. Vincent (eds.), *Handbook of Environmental Economics*, Vol I, 461-516.

[10] Kydland, Finn E. and Edward C. Prescott (1977), "Rules rather than discretion: The inconsistency of optimal plans", *Journal of Political Economy* 85: 473-491.

[11] Malcomson, James M. (1978), "Prices vs. quantities: a critical note on the use of approximations", *Review of Economic Studies* 45: 203-207.

[12] Malik, Arun S. (1991), "Permanent versus interim regulation: A game-theoretic analysis", *Journal of Environmental Economics and Management* 21: 127-139.

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

[14] Mohr, Robert D. (2006), "Environmental performance standards and the adoption of technology", *Ecological Economics* 58: 238-248.

[15] Moledina, Amyaz A., Jay S. Coggins, Stephen Polasky and Christopher Costello (2003), "Dynamic environmental policy with strategic firms: Prices versus quantities", *Journal of Environmental Economics and Management* 45: 356-376.

[16] Petrakis, Emmanuel and Anastasios Xepapadeas (2001), "To commit or not to commit: Environmental policy in imperfect markets", Department of Economics Working Paper, University of Crete.

[17] Requate, Till (2005a), "Dynamic incentives by environmental policy instruments - a survey", *Ecological Economics* 54: 175-195.

[18] Requate, Till (2005b), "Timing and commitment of environmental policy, adoption of new technology, and repercussions on R&D", *Environmental and Resource Economics* 31: 175-199.

[19] Tarui, Nori and Stephen Polasky (2005), "Environmental regulation with technology adoption, learning and strategic behavior", *Journal of Environmental Economics and Management* 50: 447-467.

[20] Watson, William D. and Ronald G. Ridker (1984), "Losses from effluent taxes and quotas under uncertainty", *Journal of Environmental Economics and Management* 11:310-326.

[21] Weitzman, Martin (1974), "Prices vs. quantities", *Review of Economic Studies* 41: 477-491.

[22] Weitzman, Martin (1978), "Reply to 'Prices vs. quantities: a critical note on the use of approximations' by James M. Malcomson", *Review of Economic Studies* 45: 209-210.

[23] Yao, Dennis A. (1988), "Strategic responses to automobile emissions control: A game-theoretic analysis", *Journal of Environmental Economics and Management* 15: 419-438.