Group Rewards and Individual Sanctions in Environmental Policy

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Summary

We examine an incentive scheme for a group of agents, where all agents are rewarded if the group meets its target. If the group does not meet its target, only the agents that meet their individual target are rewarded. In environmental policy, the EU burden sharing agreement and the UK Climate Change Agreements feature this incentive scheme. There is only a difference in outcome between group and individual rewards if emissions are stochastic. Group rewards generally lead to higher expected emissions than individual rewards. The attraction of the group reward scheme may lie in its fairness and its tough-looking targets.

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1. Introduction

Consider the following incentive scheme: A group of actors takes on a group target, which is broken down into individual targets. If the group meets its target, everyone is rewarded. If the group does not meet its target, only the agents who met their individual targets are rewarded. We are aware of two such cases in environmental policy: The EU burden sharing agreement and the UK climate change agreements.

In the Kyoto Protocol, the EU-15 as a whole committed to an 8% reduction in greenhouse gas emissions in 2008-2012 from their 1990 level. The Member States later distributed this reduction among themselves in the so-called burden sharing agreement. According to the Kyoto Protocol, all Member States will be considered to have met their targets as long as the EU as a whole achieves the 8% reduction. If the EU-wide reduction is below 8%, the Member States that did not meet their burden sharing target will be held responsible.

The UK imposed a climate change levy (CCL) on industrial energy consumers in 2001. Energy-intensive firms could get an 80% discount on the levy if they signed a Climate Change Agreement (CCA), promising to improve their energy efficiency. The government signed agreements with the sectoral organisations, and the sectoral targets were translated into targets per firm. Every other year the agreement is evaluated. If the sector meets the target laid down in the agreement, all firms in the sector (even those who didn't meet their target) continue to receive the discount for the next two years. If the sector does not meet the target, the individual firms' performance is assessed. The firms that met their target continue to receive the discount. The firms that didn't meet the target don't receive the discount for the next two years.

While our model can also be applied to the EU burden sharing agreement, we would argue it applies best to industry (as in the UK CCAs). This is mainly because we assume the players act non-cooperatively. This is probably not the best way to model interaction between EU Member States, who meet regularly to discuss and decide issues in various fields of policy. When it is clear that the EU target is in danger, because one Member State cannot meet the burden sharing target, this puts pressure on the other Member States to reduce emissions beyond their burden sharing target. This is unlikely to occur

between firms in the UK Climate Change Agreements. In addition, there is not much of a sanction for countries failing to meet their Kyoto commitments.[3]

There is only a difference between group and individual rewards (both combined with individual sanctions) if there is the possibility of individual overachievement under group rewards. Then one agent can benefit from another agent's overachievement. If each agent can set its emission level deterministically, all agents will just meet their individual targets, at least if the sanction is serious enough. In this case there is no difference between individual and group rewards.

However, it seems quite plausible to assume that there is an element of chance. Firms cannot precisely predict the effect of their measures on their emissions. It depends on factors like market and economic conditions, the weather and the functioning of abatement equipment.[4]

Stochastic pollution has not been studied much in environmental economics. Beavis and Walker (1983a) consider the regulator's problem in enforcing a percentile probabilistic constraint, where the probability that total emissions exceed a certain threshold should be below a certain percentage. They suggest a tax on the firm's average emissions and their variance. Beavis and Walker (1983b) include emission trading and a fine if the firm's estimated mean emissions exceed its permit holdings. Beavis and Dobbs (1987) further analyze percentile as well as mean probabilistic constraints. In the latter paper, as in the present paper and in Wirl and Noll (2005), the fine for exceeding the constraint is a fixed amount. Usually in the literature, the fine is increasing (typically linear) in the difference between actual and allowed emissions.[5]

Innes (2003) and Mrozek and Keeler (2004) show that tradable emission permits give firms more flexibility to handle stochastic emissions and are therefore preferable to non-tradable permits with fines for non-compliance. In a rare empirical contribution, Bandyohapdhyay and Horowitz (2006) show that US plants with higher BOD discharge variability have lower median discharges.

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[3] Officially, the sanction is that for every ton by which a country fails its target in 2008-2012, it has to abate 1.3 ton over and above its commitment for the next period. However, negotiations for the next commitment period only started in December 2005 and haven't included targets yet.
[4] When the agents are governments, there is the added uncertainty of how firms and consumers respond to government policy.

In our model, under group rewards, each firm will exert less effort to reduce its emissions than with individual rewards. This is because the whole group benefits from one firm's reduction in expected emissions. This reduction increases the probability that the industry as a whole will meet the target, so that other firms who don't meet their individual target will still escape punishment. The firms are better off with group rewards when the targets remain constant. When the targets are adjusted to yield the same level of expected industry emissions, it is not clear which system the firms will prefer.

The problem of how to get each member of a team to provide his optimal (but potentially unobservable) contribution has been widely studied, starting with Alchian and Demsetz (1972) and Holmstrom (1982). Segerson (1988) was the first to apply Holmstrom's (1982) approach to non-point pollution, where the emissions of each polluter cannot be measured and their contribution to total pollution is stochastic. She shows that the polluters can be induced to undertake the desired level of abatement by a combination of a tax/subsidy scheme for environmental quality below, respectively above, a cutoff point and a fixed fine for pollution above the cutoff point. Xepapadeas (1991), Cabe and Herriges (1992) and Horan et al. (1998) have subsequently refined the analysis of non-point pollution. Whereas the non-point pollution literature does not allow for measurement of individual emissions, the team incentive literature does compare individual to group rewards (Che and Yoo, 2001; Kvaløy and Olsen, 2006). Che and Yoo (2001) find that while individual performance evaluation does worse than joint performance evaluation in a static setting, the former may be preferred in a dynamic setting. The group rewards/individual sanctions scheme that is the focus of the present paper has not been analyzed before.

The rest of the paper is organized as follows. Section 2 discusses the UK Climate Change Agreements. The model is introduced in Section 3. Section 4 shows that with deterministic emissions, there is no difference between group and individual rewards. In Section 5 we address the difference between group and individual rewards for stochastic emissions. Section 6 concludes.

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[5] Horan (2001) examines the efficiency of several cost-effective control strategies when emissions are stochastic and environmental damage is uncertain.

2. The UK Climate Change Agreements[6]

The UK's burden sharing target is a reduction in greenhouse gas emissions of 12.5% in 2008–12 compared to 1990. The UK is one of the few OECD countries that is comfortably on course for meeting its target, thanks mainly to the "dash for gas" in the 1990s, when many electricity generators switched from coal to gas.

Following the Marshall (1998) report that advocated the use of economic instruments in climate change policy, the UK government imposed a Climate Change Levy (CCL) on industrial electricity, gas, LPG, coal and coke consumption from April 2001. The implicit rates per ton of CO_2 range from £3 for LPG via £5 for coal to £10 for electricity (Glachant and de Muizon, 2006). In April 2007 the rates will be increased for the first time (by 2.6%). They will subsequently be adjusted for inflation each year.

Energy-intensive firms could get an 80% discount on the levy when they entered into a Climate Change Agreement (CCA) with the government, promising to reduce their energy consumption. The scheme covers around 12,000 sites (5,500 companies) and 44% of total UK industry emissions (Glachant and de Muizon, 2006). The targets are mostly in relative terms (for instance in kWh primary energy use per hectolitre in the beer industry), although some sectors (aerospace, steel, supermarkets and wallcoverings) have absolute targets.[7] The targets are stated in terms of improvement over the base year (usually 1998, 1999 or 2000). These targets were agreed in so-called umbrella agreements between the government and the respective sectoral organisations in the months before the CCL came into force. The sectoral targets were subsequently translated into targets per firm in so-called underlying agreements. There are five targets for every other year from 2002 to 2010. Each milestone period runs from 1 October to 30 September. The firms then have until February of the next year to account for their emissions. Defra (the Department for the Environment, Food and Rural Affairs) evaluates the firms' performance in March and usually publishes the results around July. If the

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[6] Most information in this section, unless otherwise indicated, was taken from the Defra website http://www.defra.gov.uk/environment/ccl/index.htm, especially Defra (2003, 2005). See also de Muizon and Glachant (2004) and Glachant and de Muizon (2006) on the CCAs and OECD (2005) and Pearce (2006) on the CCL.

[7] Without additional regulation, there is the danger that firms with relative targets increase their output in order to generate allowances and sell them to firms with absolute targets, thereby raising total emissions. The so-called gateway mechanism was imposed to prevent this: a trade between firms with relative and absolute targets is allowed only if it leads to a net flow of allowances toward the relative sector.

sector as a whole meets its target, all firms in the sector are recertified and continue to receive the discount (even those who did not meet their individual target) for the next two years (starting from 1 April). If the sector does not meet the target, the individual firms' performance is assessed. The firms that met their individual target are recertified and continue to receive the discount. The firms that didn't meet the target are not recertified and don't receive the discount for the next two years.

All companies with CCA targets can participate in the UK Emission Trading Scheme (UK ETS), launched in April 2002. When the CCAs were initially negotiated, it was envisaged that emission trading would be allowed at some point, and so the CCAs contain provisions for emission trading. However it was still unclear at that point when emission trading would start and which form it would take.

When a firm overcomplies, it can notify Defra of the amount of overcompliance. This is called ringfencing of emissions. If the firm does not ringfence its emissions, they will count toward sectoral compliance. If the firm wants to sell its ringfenced emissions or retire them for its own compliance in a later period, it needs to have the emissions verified. Verification costs about £1,000 (Glachant and de Muizon, 2006). The firm then receives allowances for its ringfenced emissions.

In March 2002, the government organised a reverse auction for firms not covered by CCAs to join the ETS. These 34 so-called Direct Participants (DPs) received £215m to reduce their CO_2 emissions by 4 Mton by the end of 2006.

Table 1 summarizes the savings made by the CCA firms in the two target periods. These are the absolute savings from the emissions in the base year. According to our calculations, aggregate baseline emissions in the CCA sectors were around 90 Mton CO_2.[8] Firms in the steel sector, and especially Corus, went through a difficult time around 2001/02, experiencing a dramatic decline in output and, consequently, energy use. Since the steel sector is subject to an absolute energy target and is responsible for about a quarter of industrial primary energy use, Corus might have flooded the market with allowances, removing any energy saving incentive for all other firms. Therefore Defra negotiated stricter targets with the steel sector and did not allow Corus to sell its ringfenced emissions. Table 1 presents the original and (in brackets) the adjusted targets.

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[8] Details are available from the corresponding author upon request.

The beginning of the ETS was marked by delays in getting surplus emissions verified, causing the allowance price to rise rapidly to £12 at the end of the first compliance period (September 2002). Subsequently, allowance prices settled in the £2–5 range per ton of CO_2 (Glachant and de Muizon, 2006). Table 2 summarizes market activity. The CCA firms that were inactive in the market ringfenced 3.2 Mton in period 1 and 5.4 Mton in period 2 without having it verified yet (Glachant and de Muizon, 2006).

Table 3 summarizes the compliance results of the first two target periods. There were sectors where all target units were recertified, although the sector as a whole did not reach its target. There are two reasons for this. First, with relative targets, the sectoral target is the average of the firms' targets, weighted by their expected output. If the more energy-intensive firms produce more than expected, the sectoral target may not be met, although all firms meet their own targets. Secondly, a firm can apply for an adjustment of its target on several grounds. This adjustment, however, is only reflected in the individual, not in the sectoral target. The grounds for target adjustment are:[9]

❖ Product mix and output (PMO):
- A change in the product mix that affects overall energy use per unit.
- A reduction in throughput that leads to an increase in energy intensity, because there is a base-load component of energy use.

❖ Tolerance bands: A short delay in the implementation of an energy efficiency measure.

❖ Relevant constraints: Government requirements that have led to an increase in energy consumption, for instance an unexpected denial of planning permission.

The sectoral organizations collect the data from their members and forward them to Defra. If the sector as a whole meets the target, the sectoral organization only discloses the aggregate sectoral performance to Defra. This setup was chosen for data protection reasons and to reduce the workload to Defra. Thus, Defra does not have data on individual firms' performance in sectors that achieved their target.

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[9] PMO is only applicable to relative targets. PMO and tolerance bands are mutually exclusive, and both are only permitted for the first three milestone periods.

For the first target period, we know which percentage of firms was recertified in the sectors with incomplete recertification. The sectors and the percentages in decreasing order are: British Poultry Council poultry meat rearing 99%, ceramics (whitewares) 98%, poultry meat processing 97%, red meat processing 97%, foundries 95%, metal packaging 95%, ceramics (refractories) 93%, ceramics (materials) 91%, National Farmers Union poultry meat rearing 83%, egg production 68%.

For the Vehicle Builders and Repairers Association, "[t]here were significant errors in the original data submitted… and, following detailed study only seven participants were re-certified out of 34 with 2002 targets." (Defra, 2003) In the second milestone period, the Association terminated the CCA "for business reasons" (Defra, 2005) as did the Reprotech sector.

For the second milestone period, we don't have recertification percentages in the sectors with incomplete recertification. "All facilities except one" (Defra, 2005) were recertified in the animal feed sector. "Most facilities" were recertified in the dairy and poultry meat processing sectors. The printers sector saw "a number of facilities de-certified".

As the food and drink sector failed its overall target, facilities were tested at the sub-sector level. A number of subsectors also failed to meet their targets. The 2001 food and drink CCA lists eleven subsectors, but we don't know which subsectors met their targets and which did not. Within the subsectors that failed their targets, "a number of facilities" failed to meet their individual targets and were de-certified.

For our purposes it is interesting to find excess emission reductions, i.e. emission reductions that were not ringfenced (let alone verified). A firm's excess emission reductions are not available for sale or for its own future compliance. Instead, they count toward the sectoral target, to the benefit of other firms in the sector that failed their own target. The quantity of excess reductions is not readily available from Defra publications or Glachant and de Muizon (2006). We have compiled a lower bound estimate of excess reductions by calculating, for every sector that reached its sectoral target,[10] the difference between its actual emissions and its target adjusted for trading and ringfencing. This understates actual excess reductions for two reasons. First, for the sectors that reached

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[10] We excluded the steel sector, because as discussed above, steel firms were not allowed to sell their ringfenced emissions.

their sectoral targets, we only have the sectoral or net excess reductions. These are the difference between gross excess reductions by firms that surpassed their individual target and shortfalls by those firms that did not meet them. Secondly, we cannot include excess reductions by firms in sectors that failed their sectoral target. In this way, we arrived at a lower bound for excess reductions of 3.2 Mton in period 1 and 0.2 Mton in period 2.

Ekins and Etheridge (2006) analyse the results of the CCAs' first target period. Negotiation between government and industry led to 2010 targets between the business-as-usual (BAU) estimates and the improvements that would arise if the sector implemented all cost-effective energy efficiency measures, with both sets of estimates produced by the government's advisers (then called ETS, now called Future Energy Solutions [FES]). Ekins and Etheridge (2006), however, estimate that for most sectors, the CCA targets are hardly any stricter than BAU. They find substantial overcompliance in the first compliance period. However, they argue that the CCAs have been very useful, because they made firms aware of the potential for energy-saving measures.

The EU Emission Trading Scheme (EU ETS) for industrial CO_2 emissions, which partly overlaps the UK climate change policy mix of CCL, CCAs and Emission Trading Scheme, started on 1 January 2005.[11] The main difference between the EU ETS and the UK scheme is that the former only covers direct CO_2 emissions whereas the CCL also covers indirect CO_2 emissions (i.e. electricity use). Accordingly, the EU ETS covers the power generation sector, whereas the UK CCL does not. Conversely, some sectors (e.g. chemicals and aluminium) are covered by the UK scheme, but not by the EU ETS.

Member States could apply for their firms to opt out of the first stage of the EU ETS (2005-2007), provided that they are covered by equivalent regulation. The Commission granted an opt-out for the Direct Participants (until the scheme ended in 2006) and for the firms with a CCA. These firms could decide whether they wanted to join the EU ETS or stay in the CCA. The CCAs are set to continue for those sectors and those activities not covered by the EU ETS. Firms still have to pay the CCL when they join the EU ETS, but they only qualify for the 80% reduction if they stay in the CCA.

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[11] Boemare et al. (2003) discuss the tensions between the UK (and French) system and the EU ETS.

3. The model

We analyze the abatement choices of polluting firms in the same industry. For simplicity, we let the industry consist of two firms.

Each firm i, $i = 1, 2$, has a target $T_i > 0$ for emission reduction. We don't model the firm's output decision, so that there is no difference between relative and absolute targets.[12] The industry target T is the sum of individual targets: $T = T_1 + T_2$. Firm i undertakes abatement effort (or abatement, for short) a_i. Its cost of a_i is given by $C_i(a_i)$, with:

$$C_i'(0) = 0, \qquad C_i' > 0 \quad for \ a_i > 0, \qquad C_i'' > 0 \quad for \ a_i \geq 0 \qquad (1)$$

With deterministic emissions, firm i's emission reduction R_i equals its abatement a_i. With stochastic emissions, the firm's emissions are affected by random and uncorrelated shocks. Firm i can only affect the expected level (or more precisely, the probability distribution) of emissions through a_i.

There are several reasons why emission shocks may be correlated, either positively or negatively, among firms in the same industry. Firms in the same industry and the same country are subject to the same market and general economic conditions. Firms in the same country also face similar weather conditions. On the other hand, when one firm faces difficulties, its competitors may benefit. The former firm will see its emissions decline while the latter firms will have higher emissions.

The probability function for firm i's emission reduction R_i has the following properties:

Assumption 1. With stochastic emissions, firm i's emission reduction R_i is described by the continuous differentiable probability function $P_i(R_i - a_i)$ with support $[-\omega_i, \eta_i]$, $\omega_i > 0$, $\eta_i \geq 0$, $\lim_{x \downarrow -\omega} P(x) = 0$, and the first and highest mode at zero, i.e. $P_i(0) \geq P_i(R_i - a_i)$ for all $R_i - a_i \in [-\omega_i, \eta_i]$ and $P_i'(R_i - a_i) > 0$ for all $R_i - a_i \in (-\omega_i, 0)$.

These conditions imply that the probability function of emission reduction R_i is increasing for the lowest values of R_i. It may be increasing throughout, or have one or more modes (peaks) in the interior, as long as the first peak is the highest. Figure 1 shows a probability function with two modes. For ease of notation, we set R_i at the lowest mode

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[12] See Ebert (1998) and Boom and Dijkstra (2006) for the different effects of absolute and relative targets.

equal to the firm's abatement. The probability function has to start at zero for $a_i - \omega_i$ in order to guarantee an interior solution with individual rewards. An increase in abatement moves the probability distribution to the right, without changing its shape.

The corresponding distribution function is $D_i(R_i - a_i)$, so that $D_i(T_i - a_i)$ is the probability that firm i's emission reduction is below its individual target T_i, given that the firm abates a_i.[13] In Figure 1, this probability is given by the shaded area below the probability function to the left of T_i.

For simplicity, we disregard the possibility of emission trading. We can defend this by saying that when the CCAs were agreed, it was unclear when and how emission trading would be introduced. In the end, the Emission Trading Scheme started in April 2002, halfway through the first compliance period (Oct 2001–Sep 2002). As we saw in Section 2, delays in verification of surplus emissions led to an increase in the allowance price to £12 by September 2002. Thus, emission trading arrived late into the first compliance period and suffered from start-up problems during the remainder of this period. We can also point to the high cost of verification of ringfenced emissions (£1,000, see Section 2). With allowance prices of £2 to £5, verification is only profitable from 200 to 500 tons of CO_2. Firms might decide not to ringfence at all, especially toward the end of the programme. Our estimates of excess emission reduction (Section 2) suggest that at least in the first target period, many firms reduced emissions without ringfencing them. Our lower bound estimate of excess emission reduction in period 1 is 3.2 Mton which is a large amount compared to 3.2 Mton ringfenced but not verified, and 1.44 Mton verified.[14] Finally, we note that 12% of the firms in period 1 and 5% in period 2 were not recertified (Table 3). This means that there was a substantial number of firms that did not only fail to reach their target outright, but also chose not to make up for it by buying allowances.

The sanction for not reaching the target level of emission reduction is a fixed fine f, irrespective of the actual reduction level. In the UK CCAs, the sanction is that the firm will not receive the 80% discount on the Climate Change Levy for the next two years.[15]

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[13]As we have seen in Section 2, the UK CCAs allow for the firm's target to be relaxed in some circumstances where its emissions are higher than expected. We abstract from this possibility in our model.

[14] The amounts for period 2 are 0.2, 5.4 and 1.32 Mton, respectively.

[15] We do not explicitly take the incentive effect of the discounted levy into account. Implicitly, we have normalized a firm's abatement and its total and marginal abatement cost to zero at the point where it would operate with the discounted levy. Also, we abstract from the possibility that more abatement in period t

Under policy regime ρ, with ρ either equal to I (individual rewards) or G (group rewards), the risk-neutral firm i minimizes total cost TC_i^ρ:

$$TC_i^\rho = \pi_i^\rho(a_1, a_2)f + C_i(a_i) \qquad (2)$$

where π_i^ρ is the probability that firm i will be fined (its fine probability, for short) under policy regime ρ.

4. Deterministic emissions

With deterministic emissions, firm i's emission reduction R_i is completely determined by its abatement a_i: $R_i = a_i$. With individual rewards, firm i sets its abatement a_i equal to the target T_i if it decides to comply. Its costs of compliance are thus $C_i(T_i)$. If the firm chooses not comply, it will not abate at all and pay the fine f. We assume that $C_i(T_i) < f$, thus the firm decides to comply and sets $a_i = T_i$.

With group rewards, the group target is $T = T_1 + T_2$. Now firm i is only fined if both $a_i < T_i$ and $a_1 + a_2 < T$. Firm i's reaction function is: $a_i = min\ (T_i, T - a_j)$. Figure 2 shows the reaction functions. The unique Nash equilibrium is point A with $a_i = T_i$, $i = 1, 2$. Thus, with deterministic emissions, firms respond in the same way to individual and group rewards.

5. Stochastic emissions

5.1 Individual rewards

With individual rewards, firm i is fined if and only if its emission reduction R_i is below its individual target T_i. When the firm abates a_i, the probability that this happens is $D_i(T_i - a_i)$. Substituting this into (2), we see that the firm minimizes:

$$\min \quad TC_i^I(a_i) = D_i(T_i - a_i)f + C_i(a_i) \qquad (3)$$

where the superscript I stands for individual rewards. The first order condition is:

$$P_i(T_i - a_i)f = C_i'(a_i) \qquad (4)$$

The second order condition is:

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may make it easier to achieve the target for period $t+1$. Finally, a firm might actually benefit when its competitor is fined, because the fine increases the latter's cost of production (Salop and Scheffman, 1983). For simplicity we also abstract from this as well.

$$P_i'(T_i - a_i)f + C_i''(a_i) > 0 \tag{5}$$

On the LHS of first order condition (4) are firm i's marginal benefits MB_i^I of reducing emissions. On the RHS are its marginal abatement costs MC_i. MC_i and MB_i^I are depicted in Figure 3.[16] The MB_i^I curve has its maximum at $a_i = T_i$. We see that in this case, if the MC_i curve intersects the MB_i^I curve at all (which we assume to be the case), it will do so twice: at a_i^0 and at a_i^I.

When the firm starts to abate, there is at first no benefit, because as long as $a_i < T_i - \omega$, emission reduction will always fall short of the target T_i. Once $a_i > T_i - \omega$, there is a small probability that emission reduction will exceed the target T_i, but initially the marginal benefits of abatement reduction are below the marginal costs. This changes when abatement increases beyond the local cost maximum a_i^0. From a_i^0 to a_i^I, the marginal benefits of emission reduction exceed the marginal costs. Total costs are minimized locally at a_i^I, after which they start increasing again.

There are thus two local cost minima, one at $a_i = 0$ and one at $a_i = a_i^I$. We will assume that total costs at a_i^I are less than f, so that a_i^I is the global cost minimum.

For the most general form of the probability function that satisfies Assumption 1, there can be many solutions to (3). We will assume that the global cost minimum is always the highest a_i^I that solves (3).

Differentiating (4) totally with respect to f yields the effect of an increase in the fine:

$$\frac{da_i^I}{df} = \frac{P_i(T_i - a_i^I)}{P_i'(T_i - a_i^I)f + C_i''(a_i^I)} > 0$$

The inequality follows from (5). Differentiating (4) totally with respect to T_i, the effect of an increase in the target level of emission reduction is:

$$\frac{da_i^I}{dT_i} = \frac{P_i'(T_i - a_i^I)f}{P_i'(T_i - a_i^I) + C_i''(a_i^I)} \tag{6}$$

The denominator is positive by (5). Abatement is then increasing (decreasing) in the target when the probability function is upward (downward) sloping. Figure 4 shows the

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[16] Figures 3 to 9 were derived and drawn assuming (where applicable) that the two firms' probability and cost functions are identical and quadratic, and their targets are identical. Our formal analysis is not limited to these cases, however. The quadratic probability function has $\omega_i = \eta_i = \omega$, $i = 1,2$. Details on how to derive the Figures are available from the corresponding author upon request.

different effects that an increase in the target can have.[17] Figure 4a shows the case where abatement exceeds the target, so that the probability function is increasing. Then an increase in the target from T_i to T_i' results in an increase in abatement from a_i^I to $a_i^{I'}$. In Figure 4b abatement is below the target, and the probability function is decreasing. Now an increase in the target from T_i to T_i' results in a decrease in abatement from a_i^I to $a_i^{I'}$.

Figure 5 shows the firm's choice of abatement as a function $a_i^I(T_i)$ of the target. When the target is relatively low, abatement exceeds the target (the $a_i^I(T_i)$ curve is above the $a_i = T_i$ line). Then, as we know from (6), abatement is increasing in the target. Abatement is highest for $a_i = \overline{a}_i = \overline{T}_i$. We will call targets below $\overline{T}_i$ realistic and targets above $\overline{T}_i$ ambitious. For ambitious targets, abatement is decreasing in the target. When the target is stricter than T_i^*, the firm prefers not to abate at all and incur the fine with certainty. All abatement levels between a_i^* and $\overline{a}_i$ that can be achieved by ambitious targets can also be achieved by realistic targets. For instance, abatement level a_i' can be achieved with realistic target T_i^r and ambitious target T_i^a.

The probability function may have several modes and may thus have abatement increasing in the target for targets above $\overline{T}_i$. However, under Assumption 1 that the first peak is the highest, abatement cannot be higher than $\overline{a}_i$. Thus it is a general result that all abatement levels that can be achieved with ambitious targets can also be achieved by realistic targets.

There is then no environmental reason to choose ambitious targets. Industry obviously prefers realistic targets, because the fine probability is lower. When the government does not want to antagonize industry needlessly, it will choose realistic targets:[18]

Lemma 1. At its optimal abatement effort with individual rewards, firm i abates more than its target, so that $P_i'(T_i - a_i^I) > 0$, i.e. the probability function is upward sloping.

It seems that the targets of the UK Climate Change Agreements were realistic. It is unlikely that the same emission reduction could have been realized with more lenient targets and higher compliance, because compliance has been very high. Only 12 and 5%

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[17] Since from (4), $dMB_i/da_i = -P_i'(T_i - a_i)f$, $P_i'(T_i - a_i) > 0$ implies decreasing MB_i in Figure 4.
[18] Expected government revenues from fines are higher with ambitious targets. However, the fine is meant as a disciplining device, not as a revenue-raising device.

of firms were sanctioned for their (and their industry's) failing to meet the target in the first and second milestone period respectively (see Table 3). In all sectors that failed their sectoral target, more than half of the firms reached their individual target.

5.2 Group rewards, individual sanctions

We now examine the scheme of the UK Climate Change Agreements, where a firm is only sanctioned if both it misses its own target and its industry misses its target. The probability that firm 1 is fined under group rewards is:[19]

$$\pi_1^G = \Pr(R_1 < T_1)\Pr(R_1 + R_2 < T \mid R_1 < T_1) \tag{7}$$

i.e. the probability that its own emission reduction R_1 is below its individual target T_1 multiplied by the probability that industry reduction $R_1 + R_2$ is below the industry target $T = T_1 + T_2$, given that $R_1 < T_1$.

Define:

$$v_i \equiv T_i - a_i \qquad\qquad \tau_i \equiv R_i - a_i \qquad\qquad \tau \equiv \tau_1 + \tau_2 \tag{8}$$

Thus when $\tau_i < (>) 0$, the actual emission reduction is below (above) the abatement level. When $v_i < (>) 0$, the firm abates more than the target. By Lemma 1, $v_i < 0$ with individual rewards. In case firm 1 misses its target, τ_1 is in the range $\left[-\omega_1, v_1\right]$ while τ_2 can still be anywhere in the whole range $\left[-\omega_2, \eta_2\right]$. Substituting (8) into (7), we can write firm 1's fine probability as:

$$\pi_1^G(v_1, v_2) = \Pr(\tau_1 < v_1)\Pr(\tau < v_1 + v_2 \mid \tau_1 < v_1) \tag{9}$$

We can also write the probability as:

$$\pi_1^G(v_1, v_2) = \int_{-\omega_1 - \omega_2}^{v_1 + v_2} \overline{P}(\tau)d\tau \tag{10}$$

with $\overline{P}(\tau, v_1)$ the *scaled probability function of τ*, defined as:

$$\overline{P}(\tau, v_1) \equiv \Pr(\tau_1 < v_1)P(\tau) \tag{11}$$

where $P(\tau)$ is the probability function for $\tau = \tau_1 + \tau_2$ with $\tau_1 \in \left[-\omega_1, v_1\right]$ and $\tau_2 \in \left[-\omega_2, \eta_2\right]$. Figure 6 illustrates how to derive this scaled probability function for two

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[19] We will focus on firm 1's decision, but the analysis for firm 2 follows simply from interchanging the labels "1" and "2".

firms with identical quadratic probability functions, so that $\omega_1 = \omega_2 = \eta_2 = \omega$. For firm 2 we need the probability function over the whole range $\tau_2 \in [-\omega, \omega]$, as shown on the right of Figures 6a to c. For firm 1 we use the probability function over the range $\tau_1 \in [-\omega, v_1]$ given that $\tau_1 < v_1$, but by (9) we have to multiply this by the probability that $\tau_1 < v_1$. The relevant function is then simply the original $P_1(\tau_1)$, but only in the interval $\tau_1 \in [-\omega, v_1]$, as shown on the left of Figures 6a to c.

Figure 6a shows how to determine the probability density at a τ^* between -2ω and $v_1 - \omega$. When τ_1 is at its lowest possible value of $-\omega$, it has to be combined with $\tau_2 = \tau^* + \omega$ to achieve τ^*. A slightly higher value for τ_1 also gives τ^* when combined with an equally slightly lower value for τ_2. We can keep on increasing τ_1 and decreasing τ_2 until we come to $\tau_2 = -\omega$, which needs to be paired with $\tau_1 = \tau^* + \omega$ to achieve τ^*. Thus as we let τ_1 increase from $-\omega$ to $\tau^* + \omega$ (from light to dark in Figure 6a), the corresponding values for τ_2 decrease from $\tau^* + \omega$ to $-\omega$ (again from light to dark). For each pair of τ_1 and τ_2 we multiply the two probability densities. Finally we add them all up to obtain $P(\tau^*)$. Since $\tau_1 < v_1$, this procedure only works for $\tau^* + \omega < v_1$. Thus we have established:

$$\overline{P}(\tau^*, v_1) = \int_{-\omega}^{\tau^*+\omega} P_1(z) P_2(\tau - z) dz \qquad for \quad -2\omega < \tau^* < v_1 - \omega \tag{12}$$

Figure 6b shows how to determine the probability density at a τ' between $v_1 - \omega$ and 0. This τ' can be achieved with any value of τ_1 between $-\omega$ and v_1. The maximum τ_1 value of v_1 has to be paired with $\tau_2 = \tau' - v_1$, while the minimum τ_1 value of $-\omega$ is paired with $\tau_2 = \tau' + \omega$. This procedure works as long $\tau' + \omega$ is below the maximum τ_2 value of ω. We have thus found that:

$$\overline{P}(\tau', v_1) = \int_{-\omega}^{v_1} P_1(z) P_2(\tau' - z) dz \qquad for \quad v_1 - \omega < \tau' < 0 \tag{13}$$

Figure 6c shows how to determine the probability density at a τ'' between 0 and $v_1 + \omega$. Now τ'' is so high that it cannot be obtained with the lowest values of τ_1 anymore. The maximum value of τ_2 is ω, which has to be paired with $\tau'' - \omega > -\omega$ to obtain τ''. As before, the maximum τ_1 value of v_1 has to be paired with $\tau_2 = \tau'' - v_1$. Thus we have:

$$\overline{P}(\tau'', v_1) = \int_{\tau-\omega}^{v_1} P_1(z) P_2(\tau - z) dz \quad for \quad 0 < \tau'' < v_1 + \omega \tag{14}$$

Let us now generalize (12) to (14) for $\tau_1 \in [-\omega_1, v_1]$ and $\tau_2 \in [-\omega_2, \eta_2]$. We will first assume that $v_1 + \omega_1 < \eta_2 + \omega_2$, i.e. the range of possible emission reductions is smaller for firm 1 than for firm 2, given that firm 1 misses its individual target. This inequality is satisfied when the two distribution functions are identical, the case discussed above. The complete scaled probability function $\overline{P}(\tau, v_1)$ is then:

$$\overline{P}(\tau, v_1) = \begin{cases} \displaystyle\int_{-\omega_1}^{\tau+\omega_2} P_1(z)P_2(\tau-z)dz & for \quad -\omega_1 - \omega_2 < \tau < v_1 - \omega_2 \\ \displaystyle\int_{-\omega_1}^{v_1} P_1(z)P_2(\tau-z)dz & for \quad v_1 - \omega_2 < \tau < \eta_2 - \omega_1 \\ \displaystyle\int_{\tau-\eta_2}^{v_1} P_1(z)P_2(\tau-z)dz & for \quad \eta_2 - \omega_1 < \tau < v_1 + \eta_2 \end{cases} \tag{15}$$

In case $v_1 + \omega_1 > \eta_2 + \omega_2$, the scaled probability function is given by:

$$\overline{P}(\tau, v_1) = \begin{cases} \displaystyle\int_{-\omega_1}^{\tau+\omega_2} P_1(z)P_2(\tau-z)dz & for \quad -\omega_1 - \omega_2 < \tau < \eta_2 - \omega_1 \\ \displaystyle\int_{\tau-\eta_2}^{\tau+\omega_2} P_1(z)P_2(\tau-z)dz & for \quad \eta_2 - \omega_1 < \tau < v_1 - \omega_2 \\ \displaystyle\int_{\tau-\eta_2}^{v_1} P_1(z)P_2(\tau-z)dz & for \quad v_1 - \omega_2 < \tau < v_1 + \eta_2 \end{cases} \tag{16}$$

Firm 1's first order condition for cost minimization under group rewards is then, from (2) and (10):

$$\frac{\partial \pi_1^G(v_1, v_2)}{\partial v_1} f = f \frac{\partial}{\partial v_1} \int_{-\omega_1 - \omega_2}^{v_1 + v_2} \overline{P}(\tau, v_1)d\tau = C'(a_1) \tag{17}$$

with $\overline{P}(\tau, v_1)$ given by (15) or (16). The LHS and the middle expression give firm 1's marginal benefits of abatement MB_1^G. The RHS gives firm 1's marginal cost MC_1.

5.3 Comparing individual and group rewards

We will now examine whether group rewards lead to lower abatement than individual rewards. We then compare the firm's payoffs under the two schemes.

Under individual as well as group rewards, as shown by (4) and (17) respectively, firm 1 sets its marginal benefits of abatement equal to the marginal cost of abatement. Figure 7 shows a possible combination of firm 1's marginal cost curve MC_1 and marginal benefit

curves MB_1^I for individual rewards and MB_1^G for group rewards, given a_2^G. In the Figure, firm 1's marginal benefits are lower with group rewards. Combined with an increasing MC_1 curve, this implies that abatement is lower with group rewards. If we could prove that the MB_1^G curve for any value of a_2^G is below the MB_1^I curve, then a_1^G would be less than a_1^I for any increasing MC_1 curve. Thus we have:

Lemma 2. If the sensitivity of firm 1's fine probability π_1^ρ to its abatement a_1 is lower with group rewards G than with individual rewards I, the firm will abate less with group rewards. That is, $a_1^G < a_1^I$ if:

$$\left| \frac{\partial \pi_1^G(a_1, a_2)}{\partial a_1} \right| < \left| \frac{\partial \pi_1^I(a_1)}{\partial a_1} \right| \qquad \text{for all } a_1 \in [T_1, T_1 + \omega_1] \tag{18}$$

We will now check whether inequality (18) holds. With individual rewards, the effect of a marginal decrease in v_1 on the fine probability is $P_1(v_1)$ as we know from (4) and (8). Thus we have to examine the effect with group rewards and relate it to $P_1(v_1)$.

When firm 2 does not abate at all in the Nash equilibrium of group rewards, it will certainly fail its individual target.[20] Then for firm 1, there is no difference between individual and group rewards, so that it will abate the same amount under both schemes. This is not a very interesting case.

The situation is similar when firm 2 abates a positive amount, but will always fail its individual target. Again, firm 2 will not overachieve, which leads firm 1 to abate the same under individual and group rewards.

Let us now return to the case where the two firms have identical quadratic probability functions so that $\omega_1 = \omega_2 = \eta_2 = \omega$.[21] When firm 2 abates so much that it may reach its individual target, $v_2 < \omega$. There is no point for firm 2 to abate beyond the point where it will reach its individual target for certain. Thus $v_2 > -\omega$. Then by (15), $v_1 + v_2$ is either in the second or the third interval of τ.

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[20] If there were a possibility that firm 2 could reach its individual target without abatement, then at zero abatement it would have positive marginal benefits and zero marginal cost of abatement. Then firm 2 would abate a positive amount.

[21] The formal analysis for the general case is in the Appendix.

Let us first examine the case where $v_1 + v_2$ is in the second interval. We illustrated in Figure 6a how to calculate the scaled probability function $\overline{P}(\tau)$ in the first interval of τ between -2ω and $v_1 - \omega$. When v_1 falls, the highest value $v_1 - \omega$ can no longer be obtained, i.e. we lose $\overline{P}(v_1 - \omega)$. Figure 6b illustrated how to calculate $\overline{P}(\tau)$ in the second interval of τ between $v_1 - \omega$ and 0, which contains $v_1 + v_2$. When v_1 falls, three things change in the second interval. First, the lower bound $v_1 - \omega$ of the interval decreases, so that we gain $\overline{P}(v_1 - \omega)$. This offsets the loss of $\overline{P}(v_1 - \omega)$ in the first interval. Secondly, any τ value in the interior of the second interval can now no longer be obtained by adding up $\tau_1 = v_1$ and $\tau_2 = \tau - v_1$. For every τ, we lose $P_1(v_1)$ multiplied by $P_2(\tau - v_1)$. Figure 8a illustrates how to calculate this loss. The lowest τ value of $v_1 - \omega$ is achieved with $\tau_1 = v_1$ plus $\tau_2 = -\omega$. The highest τ value of $v_1 + v_2$ is achieved with $\tau_1 = v_1$ plus $\tau_2 = v_2$. The loss is then $P_1(v_1)$ multiplied by the area $WSKJ$ under the $P_2(v_2)$ curve from $-\omega$ to v_2.

The third and final change in the second interval is that the higher bound $v_1 + v_2$ decreases, so that we lose $\overline{P}(v_1 + v_2)$. Figure 8b illustrates how to find this $\overline{P}(v_1 + v_2)$. Analogously to Figure 6b, the minimum τ_1 value of $-\omega$ results in $v_1 + v_2$ when combined with the τ_2 value of $v_1 + v_2 + \omega$. The maximum τ_1 value of v_1 has to be combined with $\tau_2 = v_2$ to yield $v_1 + v_2$. Because the $P_1(\tau_1)$ curve is increasing in the interval $[-\omega, v_1]$, all values of $P_1(\tau_1)$ are less than or equal to $P_1(v_1)$. The value for $\overline{P}(v_1 + v_2)$ is then less than $P_1(v_1)$ times the shaded area $JKLM$ under the $P_2(\tau_2)$ curve from v_2 to $v_1 + v_2 - \omega$.

The decrease in firm 1's fine probability under group rewards resulting from a marginal decrease in v_1 is then less than $P_1(v_1)$ multiplied by the areas $WSKJ + JKLM$ in Figure 8. The combined area of $WSLM$ is less than the total area of $WSW^* = 1$ under the $P_2(v_2)$ curve, because point M is to the left of point W^* since $v_1 + v_2 \leq 0$ in the second interval of τ. The marginal effect of abatement on the fine probability is thus less with group rewards than with individual rewards.

Now let us examine the case where $v_1 + v_2$ is in the third interval of τ. Again, we lose $\overline{P}(v_1 - \omega)$ in the first interval, but regain it in the second interval. The upper bound of the second interval remains at 0. As before, for every τ in the interior of the second interval, we lose $P_1(v_1)$ multiplied by $P_2(\tau - v_1)$. The lowest τ value of $v_1 - \omega$ is again achieved with

$\tau_1 = v_1$ plus $\tau_2 = -\omega$. The highest τ value is now 0, which is achieved with $\tau_1 = v_1$ plus $\tau_2 = -v_1$. The loss is then $P_1(v_1)$ multiplied by the area *WSRG* in Figure 9 under the $P_2(v_2)$ curve from $-\omega$ to $-v_1$.

Two things change in the third interval of τ. First, for every τ in the interior we lose $P_1(v_1)$ multiplied by $P_2(\tau-v_1)$. The lowest τ value of 0 is achieved with $\tau_1 = v_1$ plus $\tau_2 = -v_1$. The highest τ value of $v_1 + v_2$ is achieved with $\tau_1 = v_1$ plus $\tau_2 = v_2$. The loss is then $P_1(v_1)$ multiplied by the area *GRKJ* in Figure 9 under the $P_2(v_2)$ curve from $-v_1$ to v_2.

The other change in the third interval is that the highest τ value of $v_1 + v_2$ can now no longer be obtained, so that we lose $\overline{P}(v_1 + v_2)$. Analogously to Figure 6c, the maximum τ_1 value of v_1 has to be combined with $\tau_2 = v_2$ to yield $v_1 + v_2$. The maximum τ_2 value of ω results in $v_1 + v_2$ when combined with the τ_1 value of $v_1 + v_2 - \omega$. Because the $P_1(\tau_1)$ curve is increasing in the interval $[v_1+v_2-\omega, v_1]$, all values of $P_1(\tau_1)$ are less than or equal to $P_1(v_1)$. The value for $\overline{P}(v_1 + v_2)$ is then less than $P_1(v_1)$ times the shaded area *JKW** under the $P_2(\tau_2)$ curve from v_2 to ω.

The decrease in firm 1's fine probability under group rewards resulting from a marginal decrease in v_1 is then less than $P_1(v_1)$ multiplied by the areas *WSRG + GRKJ + JKW**. These areas add up to *WSW** = 1. Again, the marginal effect of abatement on the fine probability is less with group rewards than with individual rewards.

Formally, we can show:[22]

Proposition 1. In the Nash equilibrium under group rewards, let both firms have a positive probability of reaching their individual target. Then both firms abate less with group rewards than with individual rewards.

Finally, let us compare a firm's total cost under individual and group rewards. When the targets are the same under both regimes, we can write:

$$TC_1^I\left(a_1^I\right) = D_1(T_1 - a_1^I)f + C_1(a_1^I) >$$
$$> D_1(T_1 - a_1^I)\Pr\left(R_1^I + R_2^G < T \mid R_1^I < T_1\right)f + C_1\left(a_1^I\right) > \pi_1^G f + C_1\left(a_1^G\right) = TC_1^G\left(a_1^G, a_2^G\right)$$

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[22] The proof is in the Appendix.

The first inequality follows from $Pr(R_1^I + R_2^G < T_1' \mid R_1^I < T_1) < 1$ and the second inequality from the fact that a_1^G minimizes firm 1's total cost with group rewards, given a_2^G.[23]

When the government realizes that group rewards lead to less abatement than individual rewards, it may wish to set stricter targets under group rewards. Then it is unclear which system firms would prefer. On the one hand, the probability that a firm misses its individual target is now higher under group rewards. On the other hand, even if the firm misses its individual target, it might not be fined with group rewards.

6. Conclusion

In this paper, we have examined the incentive system of group rewards and individual sanctions, as applied in the UK Climate Change Agreements. Each firm has an individual energy saving target, but there are also sectoral targets. Every other year, the firms' performance is evaluated. If the sector as a whole meets its target, all firms in the sector continue to receive the 80% discount on the Climate Change Levy for the next two years. If the sector does not meet its target, only the firms that met their individual targets continue to receive the discount.

We have compared this system of group rewards to individual rewards. When the firms' actions determine their emissions exactly, there is no difference between the two systems. There is a difference when emissions are stochastic. A firm will abate less under group rewards than under individual rewards if its probability distribution of emission reduction is single-peaked, or at least the first peak is the highest.

When group rewards lead to less effort than individual rewards, one might wonder why the government (or in a more general setting, the principal) would want to use group rewards. One reason may be that group performance is easier to observe than individual performance, or it is difficult to relate group performance to individual performance. This would be the case, for instance, with a football team. However, in the case of the Climate Change Agreements, the sectoral organisations collect the data on individual firms' performances from the firms and collate these to calculate the sector's performance. Thus the information on individual performance has to be available in order to establish the

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[23] Note that both inequalities would also hold if abatement were higher under group rewards.

group's performance. This means that there is no informational reason for the government to rely on group rewards.

We can see two other possible advantages of group rewards. The first advantage is fairness. When emissions are stochastic, individual rewards can be regarded as unfair. Two identical firms can take exactly the same abatement measures, yet one is punished because it pollutes too much, while the other reaches the emission reduction target and is rewarded. Reward or punishment is down to luck. The group reward scheme is fairer, because one firm's unintentional underachievement can be compensated by another firm's unintentional overachievement. The probability that one firm is punished while the other is not is lower with group rewards. In that sense, group rewards are fairer than individual rewards.

The second advantage of group rewards is that there is something in it for everyone, for the government as well as for industry. The government can point to a set of targets that look quite ambitious. However, firms in the polluting industry know that even if they do not meet their individual target, they may still escape the fine.

Appendix. Proof of Proposition 1

Without loss of generality, let us consider firm 1. By Lemma 2 and using (4) and (8), firm 1's abatement under group rewards is lower than under individual rewards if and only if:

$$\frac{\partial \pi_1^G (v_1, v_2)}{\partial v_1} < \frac{\partial \pi_1^I (v_1)}{\partial v_1} = P_1(v_1) \qquad (A.1)$$

for all $v_1 \in (-\omega_1, 0)$. When firm 2 abates so much that it may reach its individual target, $v_2 < \eta_2$. Should firm 2 want to achieve $\Pr(\tau_2 < v_2) = 1$, it will do so with the highest possible v_2 of $-\omega_2$, so that $v_2 \geq -\omega_2$.

We have to consider the following cases:

1. $v_1 + \omega_1 < \eta_2 + \omega_2$ and
a. $v_1 - \omega_2 \leq v_1 + v_2 \leq \eta_2 - \omega_1$
b. $\eta_2 - \omega_1 < v_1 + v_2 < v_1 + \eta_2$
2. $v_1 + \omega_1 \geq \eta_2 + \omega_2$

Case 1a. In this case, $v_1 + v_2$ is in the second interval of $\overline{P}(\tau, v_1)$ in (15). Then from (15) and (17):

$$\frac{\partial \pi_1^G(v_1, v_2)}{\partial v_1} = \frac{\partial}{\partial v_1} \int_{-\omega_1 - \omega_2}^{v_1 - \omega_2} \overline{P}(\tau)d\tau + \frac{\partial}{\partial v_1} \int_{v_1 - \omega_2}^{v_1 + v_2} \overline{P}(\zeta)d\zeta \tag{A.2}$$

For the first term on the RHS of (A.2) we find from (15):

$$\frac{\partial}{\partial v_1} \int_{-\omega_1 - \omega_2}^{v_1 - \omega_2} \overline{P}(\tau)d\tau = \overline{P}(v_1 - \omega_2) \tag{A.3}$$

For the second term on the RHS of (A.2) we find from (15):

$$\frac{\partial}{\partial v_1} \int_{v_1 - \omega_2}^{v_1 + v_2} \overline{P}(\zeta)d\zeta = -\overline{P}(v_1 - \omega_2) + \int_{v_1 - \omega_2}^{v_1 + v_2} P_1(v_1)P_2(\zeta - v_1)d\zeta + \overline{P}(v_1 + v_2) \tag{A.4}$$

where the second term on the RHS can be rewritten as:

$$\int_{v_1 - \omega_2}^{v_1 + v_2} P_1(v_1)P_2(\tau - v_1)d\tau = P_1(v_1) \int_{-\omega_2}^{v_2} P_2(y)dy \tag{A.5}$$

For the third term on the RHS of (A.4):

$$\overline{P}(v_1 + v_2) = \int_{-\omega_1}^{v_1} P_1(z)P_2(v_1 + v_2 - z)dz < P_1(v_1) \int_{-\omega_1}^{v_1} P_2(v_1 + v_2 - z)dz = P_1(v_1) \int_{v_2}^{v_1 + v_2 + \omega_1} P_2(x)dx$$

The inequality follows from $P_1(v_1) > P_1(z)$ for all $z < v_1$ by Assumption 1 and $v_1 < 0$ from Lemma 1. Since $v_1 + v_2 \leq \eta_2 - \omega_1$ in the second interval of τ, we can write:

$$\overline{P}(v_1 + v_2) < P_1(v_1) \int_{v_2}^{v_1 + v_2 + \omega_1} P_2(x)dx \leq P_1(v_1) \int_{v_2}^{\eta_2} P_2(x)dx \tag{A.6}$$

Substituting (A.3) to (A.6) into (A.2):

$$\frac{\partial \pi_1^G(v_1, v_2)}{\partial v_1} = P_1(v_1) \int_{-\omega_2}^{v_2} P_2(y)dy + \overline{P}(v_1 + v_2) < P_1(v_1) \left[\int_{-\omega_2}^{v_2} P_2(y)dy + \int_{v_2}^{\eta_2} P_2(x)dx \right] = P_1(v_1)$$

Thus inequality (A.1) is satisfied in Case 1a.

Case 1b. In this case, $v_1 + v_2$ is in the third interval of $\overline{P}(\tau, v_1)$ in (15). Then from (15) and (17):

$$\frac{\partial \pi_1^G(v_1, v_2)}{\partial v_1} = \frac{\partial}{\partial v_1} \int_{-\omega_1 - \omega_2}^{v_1 - \omega_2} \overline{P}(\tau)d\tau + \frac{\partial}{\partial v_1} \int_{v_1 - \omega_2}^{\eta_2 - \omega_1} \overline{P}(\zeta)d\zeta + \frac{\partial}{\partial v_1} \int_{\eta_2 - \omega_1}^{v_1 + v_2} \overline{P}(\theta)d\theta \tag{A.7}$$

From (A.3) and adapting (A.4) and (A.5), we have for the first two terms on the RHS:

$$\frac{\partial}{\partial v_1}\int_{-\omega_1-\omega_2}^{v_1-\omega_2}\overline{P}(\tau)d\tau + \frac{\partial}{\partial v_1}\int_{v_1-\omega_2}^{\eta_2-\omega_1}\overline{P}(\xi)d\xi = P_1(v_1)\int_{-\omega_2}^{\eta_2-\omega_1-v_1}P_2(y)dy \tag{A.8}$$

From (15), the third term on the RHS of (A.7) can be written as:

$$\frac{\partial}{\partial v_1}\int_{\eta_2-\omega_1}^{v_1+v_2}\overline{P}(\theta)d\theta = \int_{\eta_2-\omega_1}^{v_1+v_2}P_1(v_1)P_2(v_1+v_2-z)dz + \overline{P}(v_1+v_2) \tag{A.9}$$

For the first term on the RHS of (A.9), we have:

$$\int_{\eta_2-\omega_1}^{v_1+v_2}P_1(v_1)P_2(\tau-v_1)dz = P_1(v_1)\int_{\eta_2-\omega_1-v_1}^{v_2}P_2(x)dx \tag{A.10}$$

For the second term on the RHS of (A.9):

$$\overline{P}(v_1+v_2) = \int_{v_1+v_2-\eta_2}^{v_1}P_1(z)P_2(v_1+v_2-z)dz < P_1(v_1)\int_{v_1+v_2-\eta_2}^{v_1}P_2(v_1+v_2-z)dz = P_1(v_1)\int_{v_2}^{\eta_2}P_2(\zeta)d\zeta \tag{A.11}$$

The inequality follows from $P_1(v_1) > P_1(z)$ for all $z < v_1$ by Assumption 1 and $v_1 < 0$ from Lemma 1. Substituting (A.8) to (A.11) into (A.7):

$$\frac{\partial\pi_1^G(v_1,v_2)}{\partial v_1} < P_1(v_1)\left[\int_{-\omega}^{\eta_2-\omega_1-v_1}P_2(y)dy + \int_{\eta_2-\omega_1-v_1}^{v_2}P_2(x)dx + \int_{v_2}^{\omega_2}P_2(\zeta)d\zeta\right] = P_1(v_1)$$

Thus inequality (A.1) is also satisfied in Case 1b.

Case 2. In this case, $v_1 + v_2$ is in the third interval of $\overline{P}(\tau,v_1)$ in (16). Then from (16) and (17):

$$\frac{\partial\pi_1^G(v_1,v_2)}{\partial v_1} = \frac{\partial}{\partial v_1}\int_{\eta_2-\omega_1}^{v_1-\omega_2}\overline{P}(\tau)d\tau + \frac{\partial}{\partial v_1}\int_{v_1-\omega_2}^{v_1+v_2}\overline{P}(\zeta)d\zeta = \int_{v_1-\omega_2}^{v_1+v_2}P_1(v_1)P_2(\zeta-v_1)d\zeta + \overline{P}(v_1+v_2) \tag{A.12}$$

The first term on the RHS can be rewritten as:

$$\int_{v_1-\omega_2}^{v_1+v_2}P_1(v_1)P_2(\zeta-v_1)d\zeta = P_1(v_1)\int_{-\omega_2}^{v_2}P_2(y)dy \tag{A.13}$$

The second term on the RHS of (A.12) can be written as:

$$\overline{P}(v_1+v_2) = \int_{v_1+v_2-\eta_2}^{v_1}P_1(z)P_2(v_1+v_2-z)dz < P_1(v_1)\int_{v_1+v_2-\eta_2}^{v_1}P_2(v_1+v_2-z)dz = P_1(v_1)\int_{v_2}^{\eta_2}P_2(x)dx \tag{A.14}$$

The inequality follows from $P_1(v_1) > P_1(z)$ for all $z < v_1$ by Assumption 1 and $v_1 < 0$ from Lemma 1. Substituting (A.13) and (A.14) into (A.12):

$$\frac{\partial \pi_1^G(v_1, v_2)}{\partial v_1} < P_1(v_1) \left[\int_{-\omega_2}^{v_2} P_2(y)dy + \int_{v_2}^{\eta_2} P_2(x)dx \right] = P_1(v_1)$$

Thus in Case 2 as well, inequality (A.1) is satisfied.

References

Alchian, Armen A. and Harold Demsetz (1972), "Production, information costs, and economic organization", American Economic Review 62: 777-795.

Bandyopadhyay, Sushenjit and John Horowitz (2006), "Do plants overcomply with water pollution regulations? The role of discharge variability", Topics in Economic Analysis and Policy 6(1), Article 4.

Beavis, Brian and Ian Dobbs (1987), "Firm behaviour under regulatory control of stochastic environmental waste by probabilistic constraints", Journal of Environmental Economics and Management 14: 112-127.

Beavis, Brian and Martin Walker (1983a), "Achieving environmental standards with stochastic discharges", Journal of Environmental Economics and Management 10: 103-111.

Beavis, Brian and Martin Walker (1983b), "Random wastes, imperfect monitoring and environmental quality standards", Journal of Public Economics 21: 377-387.

Boemare, Catherine, Philippe Quirion and Steve Sorrell (2003), "The evolution of emissions trading in the EU: Tensions between national trading schemes and the proposed EU directive", Climate Policy 3S2: S105-S124.

Boom, Jan-Tjeerd and Bouwe R. Dijkstra (2006), "Permit trading and credit trading: A comparison of cap-based and rate-based emissions trading under perfect and imperfect competition", Discussion paper 06/10, School of Economics, University of Nottingham.

Cabe, Richard and Joseph A. Herriges (1992), "The regulation of non-point-source pollution under imperfect and asymmetric information", Journal of Environmental Economics and Management 22: 134-146.

Che, Yeon-koo and Seung-Weon Yoo (2001), "Optimal incentives for teams", American Economic Review 91: 525-541.

Department for the Environment, Food and Rural Affairs (Defra) (2003), Climate Change Agreements – Results of the First Target Period Assessment, http://www.defra.gov.uk/environment/ccl/pdf/cca_aug04.pdf.

Department for the Environment, Food and Rural Affairs (Defra) (2005), Climate Change Agreements – Results of the Second Target Period Assessment, http://www.defra.gov.uk/environment/ccl/pdf/cca_jul05.pdf.

de Muizon, Gildas and Matthieu Glachant (2004), "The UK Climate Change Levy Agreements: Combining negotiated agreements with tax and emission trading", in: A. Baranzini and P. Thalmann (eds), *Voluntary Approaches to Climate Protection: An Economic Assessment of Private-Public Partnership,* Edward Elgar, Cheltenham (UK), 231-248.

Ebert, Udo (1998), "Relative standards: A positive and normative analysis", Journal of Economics 67: 17-38.

Ekins, Paul and Ben Etheridge (2006), "The environmental and economic impacts of the UK climate change agreements", Energy Policy 34: 2071-2086.

Glachant, Mathieu and Gildas de Muizon (2006), "Climate Change Agreements in the UK: A successful policy experience?", mimeo, CERNA, Paris.

Holmstrom, Bengt (1982), "Moral hazard in teams", Bell Journal of Economics 13: 324-340.

Horan, Richard D. (2001), "Cost-effective and stochastic dominance approaches to stochastic pollution control", Environmental and Resource Economics 18: 373-389.

Horan, Richard D., James S. Shortle and David G. Abler (1998), "Ambient taxes when polluters have multiple choices", Journal of Environmental Economics and Management 36: 186-199.

Innes, Robert (2003), "Stochastic pollution, costly sanctions, and optimality of emission permit banking", Journal of Environmental Economics and Management 45: 546-568.

Kvaløy, Ola and Trond E. Olsen (2006), "Team incentives in relational employment contracts", Journal of Labor Economics 24: 139-169.

Marshall, Lord (1998), "Economic instruments and the business use of energy", Report to the Chancellor of the Exchequer, London.

Mrozek, Janusz R. and Andrew G. Keeler (2004), "Pooling of uncertainty: Enforcing tradable permits regulation when emissions are stochastic", Environmental and Resource Economics 29: 459-481.

OECD (2005), The United Kingdom Climate Change Levy: A Study in Political Economy, Paper of the Environment Directorate, Centre for Tax Policy and Administration, Paris.

Pearce, David (2006), "The political economy of an energy tax: The United Kingdom's Climate Change Levy", Energy Economics 28: 149-158.

Salop, Stephen C. and David T. Scheffman (1983), "Raising rivals' costs", American Economic Review 73: 267-271.

Segerson, Kathleen (1988), "Uncertainty and incentives for nonpoint pollution control", Journal of Environmental Economics and Management 15: 87-98.

Wirl, Franz and Jürgen Noll (2005), "Abatement and permits when pollution is uncertain and violations are fined", Working paper, Department of Business Studies, University of Vienna.

Xepapadeas, Anastasios (1991), "Environmental policy under imperfect information: Incentives and moral hazard", Journal of Environmental Economics and Management 20: 113-126.

Tables

Table 1. Absolute savings from baseline, Mt CO_2 per annum (with adjusted steel targets)

	Actual	Target	Actual minus target
Target Period 1	15.8	6.0 (12.3)	9.8 (3.5)
Target Period 2	14.4	5.5 (9.3)	8.9 (5.1)

Source: Defra (2005)

Table 2. Market behaviour of UK ETS participants

	Number of firms	Allocation* (1)	Retirement* (2)	Net allocation* (1) – (2)	Net sales (3)	Banking (1)–(2)–(3)
CCA firms	**1243**	**2.76**	**1.35**	**1.41**	**–0.95**	**2.37**
Sellers	207	2.73	0.24	2.49	0.58	1.91
Buyers	1036	0.03	1.11	–1.08	–1.53	0.46
Period 1		1.44	0.59	0.85	–0.60	1.32
Period 2		1.32	0.76	0.56	–0.36	0.92
DPs	**31**	**59.54**	**52.38**	**7.16**	**0.92**	**6.24**

*Mton CO_2 Source: Glachant and de Muizon (2006), Table 3

Table 3. UK CCAs: Compliance results from the first two milestone periods

	2002	2004
Number of sectors with:		
• Sectoral target met	24	19
• All firms recertified	35	41
• Not all firms recertified	11	5
Number of target units:		
• Recertified	5,042 (88%)	4,420 (95%)
• Not recertified	219	23
• Left the agreement	164	228
• Did not submit data	317	4

Note: Five subsectors of ceramics (with no sectoral target) treated as sectors

Source: Compiled from Defra (2003, 2005)

Figures
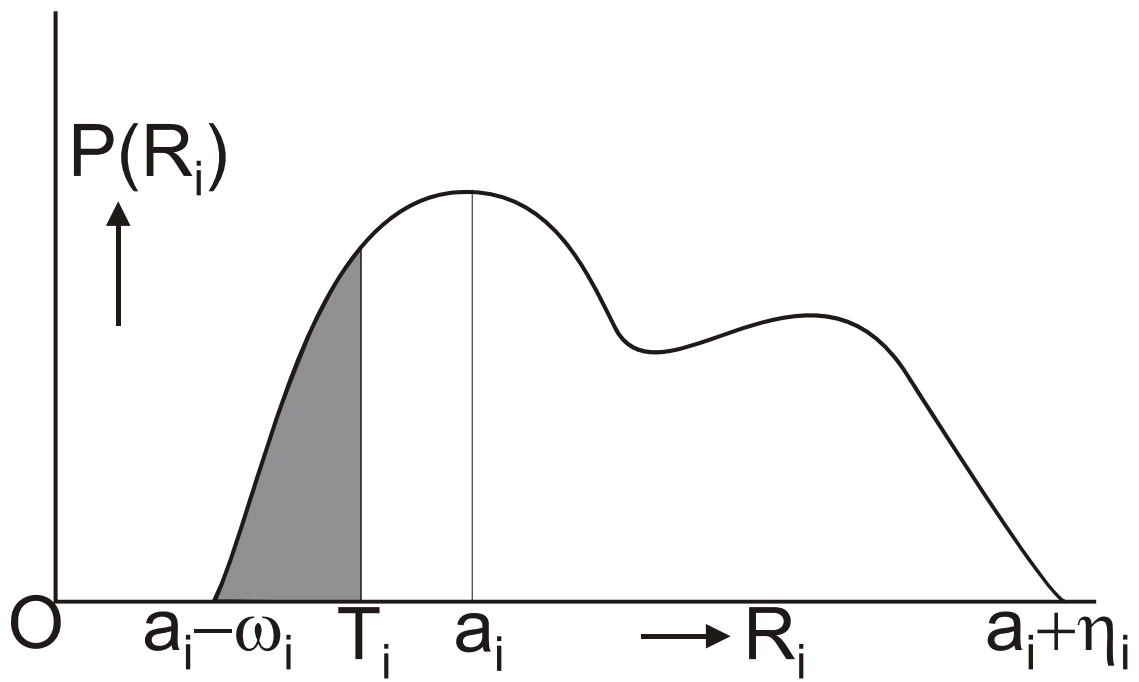
Figure 1. A probability function for firm i's emission reduction R_i
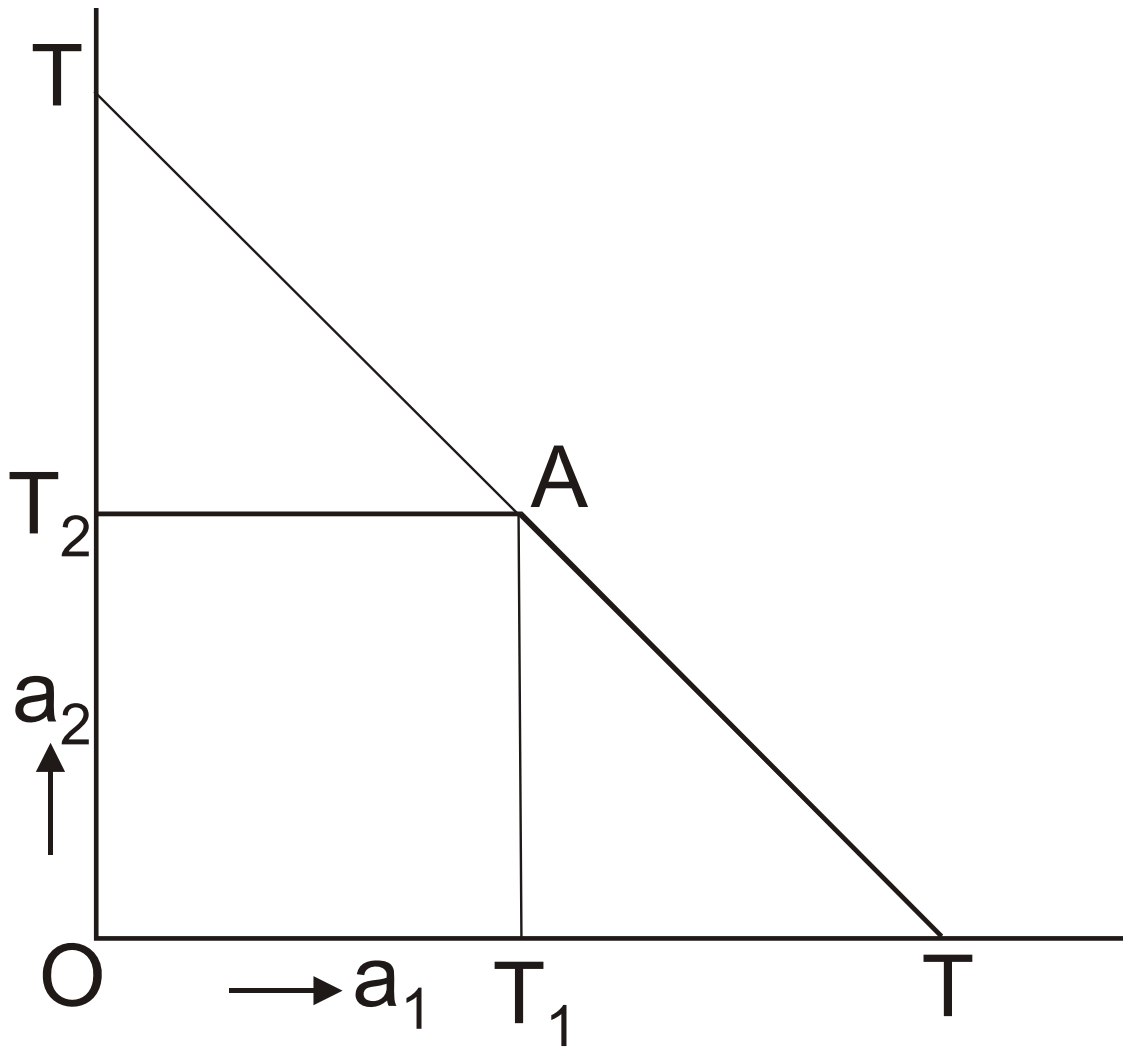
Figure 2. Firms 1 and 2's reaction functions (thin and thick line, respectively) with deterministic emissions and group rewards
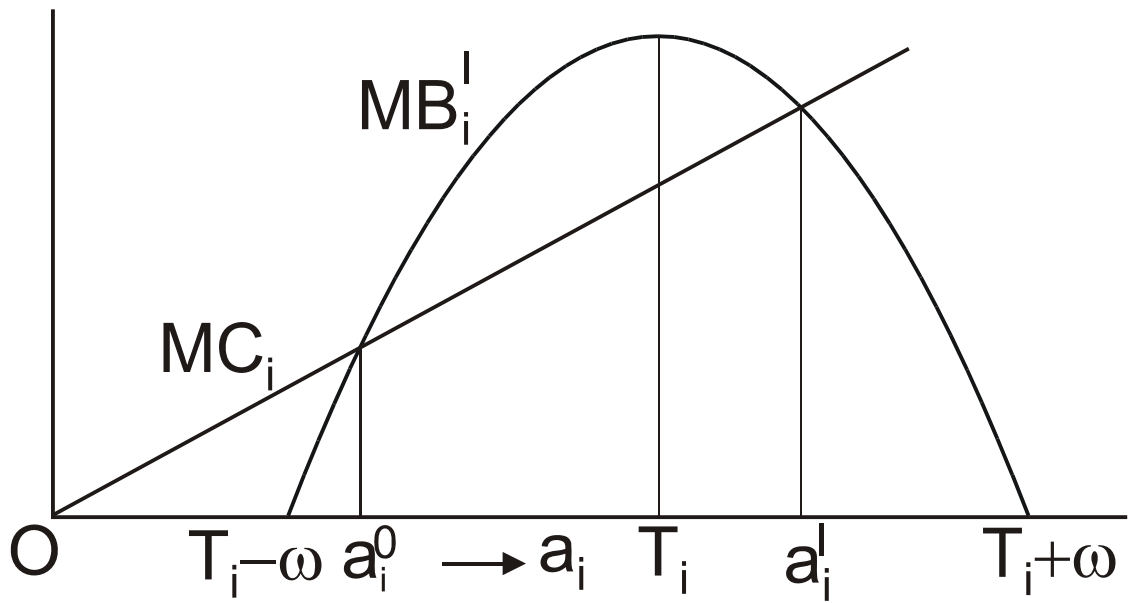
Figure 3. Marginal benefits and marginal costs of abatement with individual rewards I
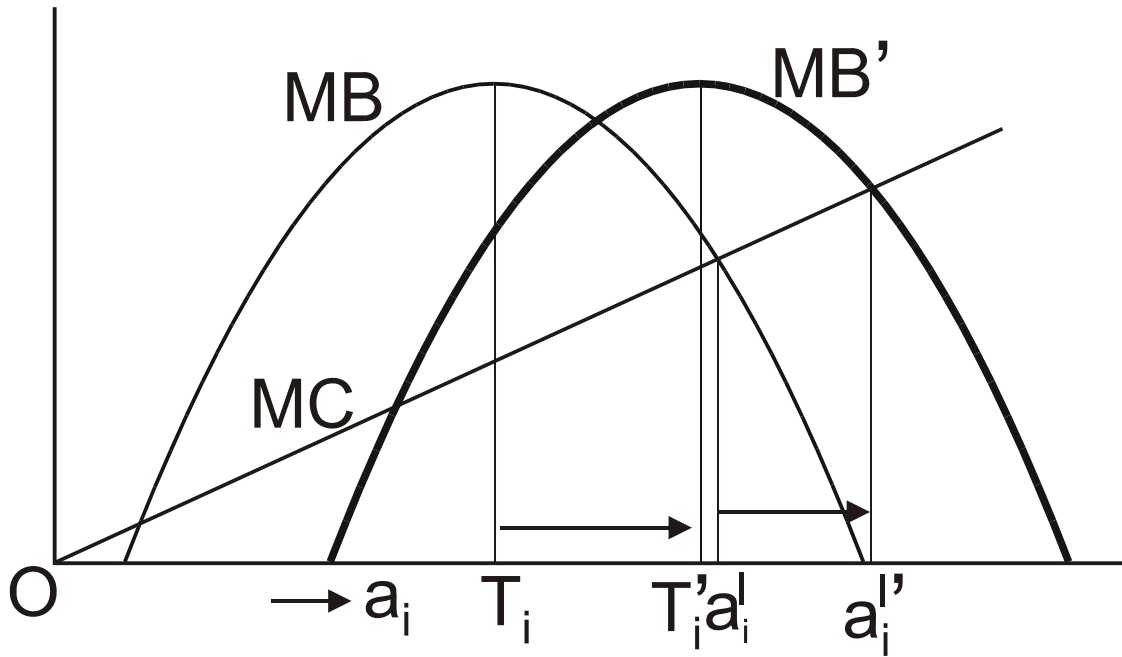
(a) Abatement above target
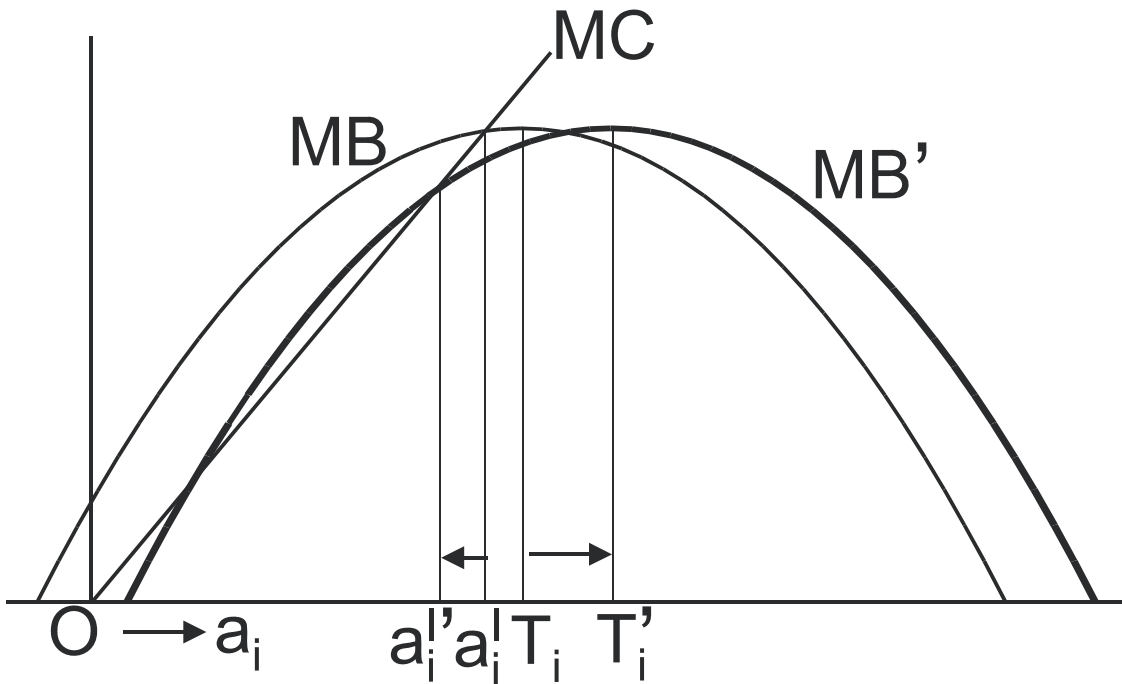
(b) Abatement below target

Figure 4. The effect of a change in firm i's target T_i on its abatement a_i^I
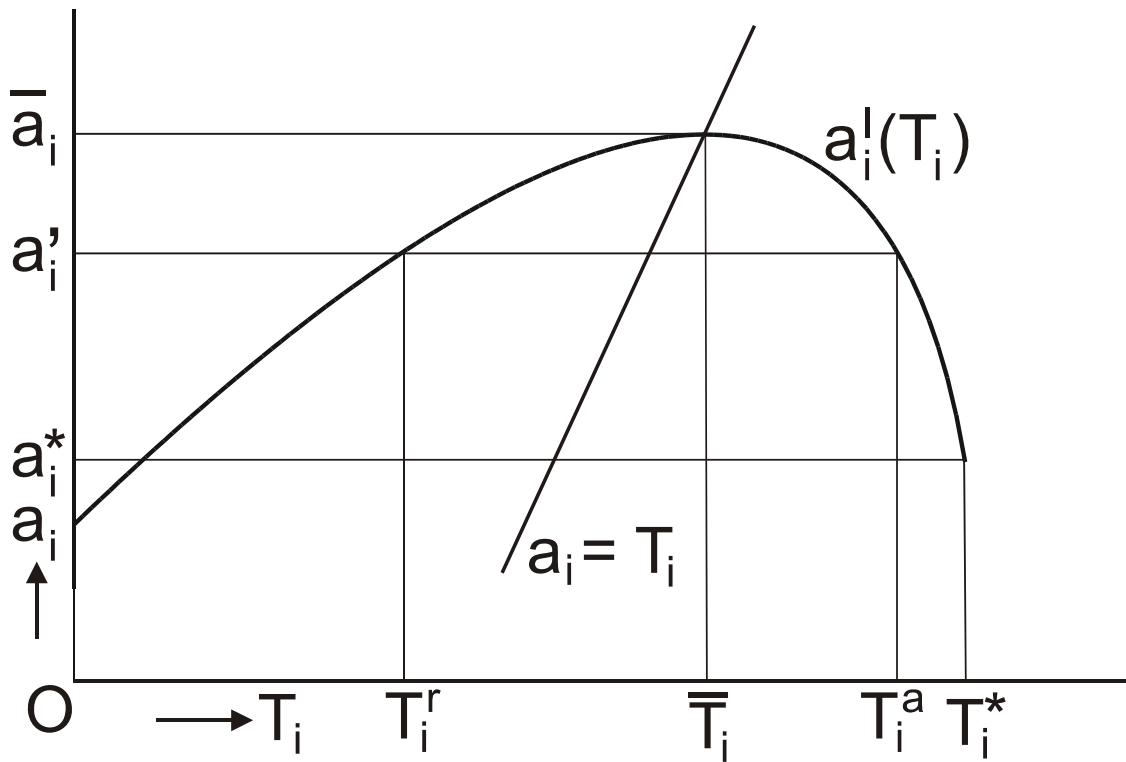
Figure 5. Firm i's abatement a_i^I under individual rewards as a function of the target T_i
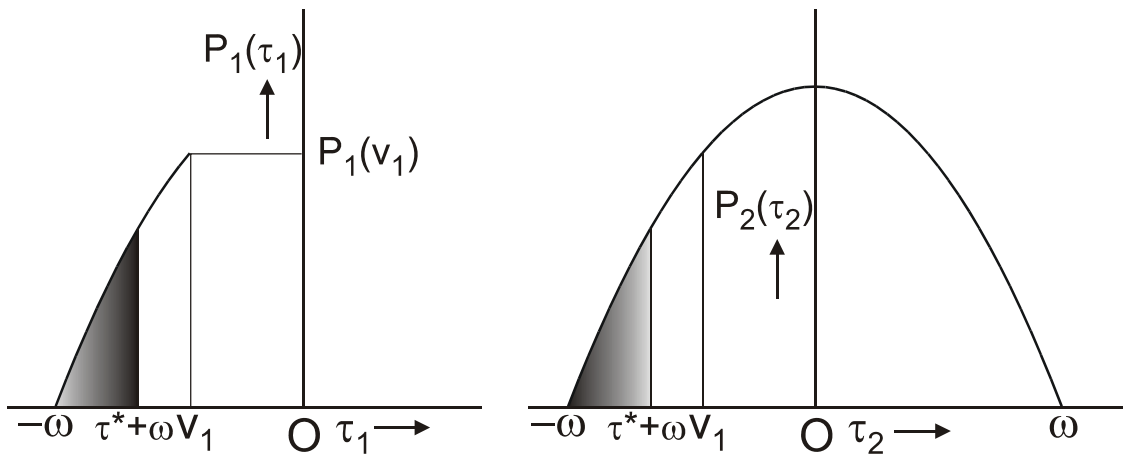
(a) $\overline{P}(\tau^*)$ with $-2\omega < \tau^* < v_1 - \omega$
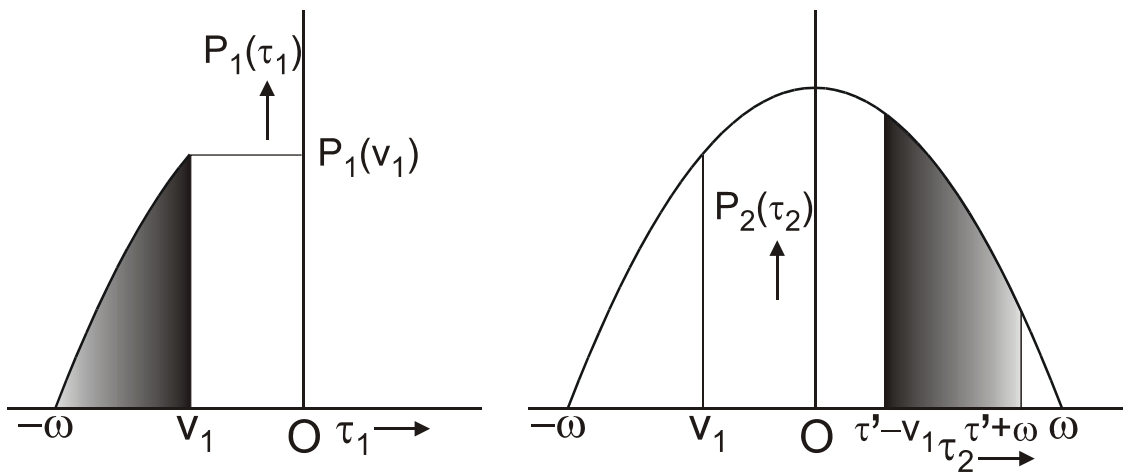
(b) $\overline{P}(\tau')$ with $v_1 - \omega < \tau' < 0$
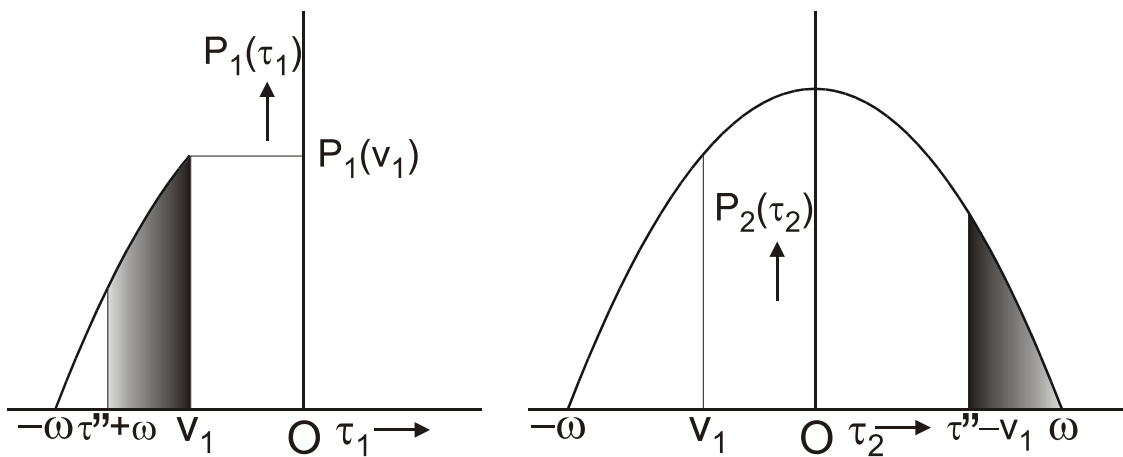
(c) $\overline{P}(\tau'')$ with $0 < \tau'' < v_1 + \omega$

Figure 6. Deriving the scaled probability function $\overline{P}(\tau)$ of $\tau = \tau_1 + \tau_2$
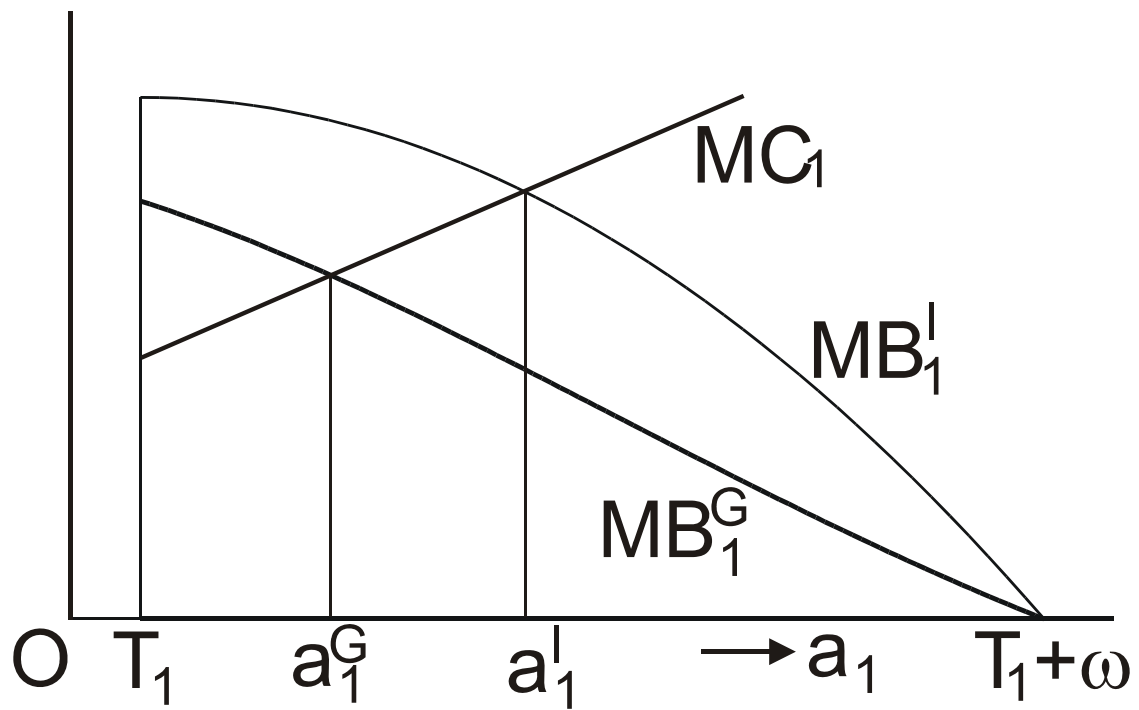
Figure 7. Firm 1's abatement under group rewards $a_1{}^G$ and individual rewards $a_1{}^I$
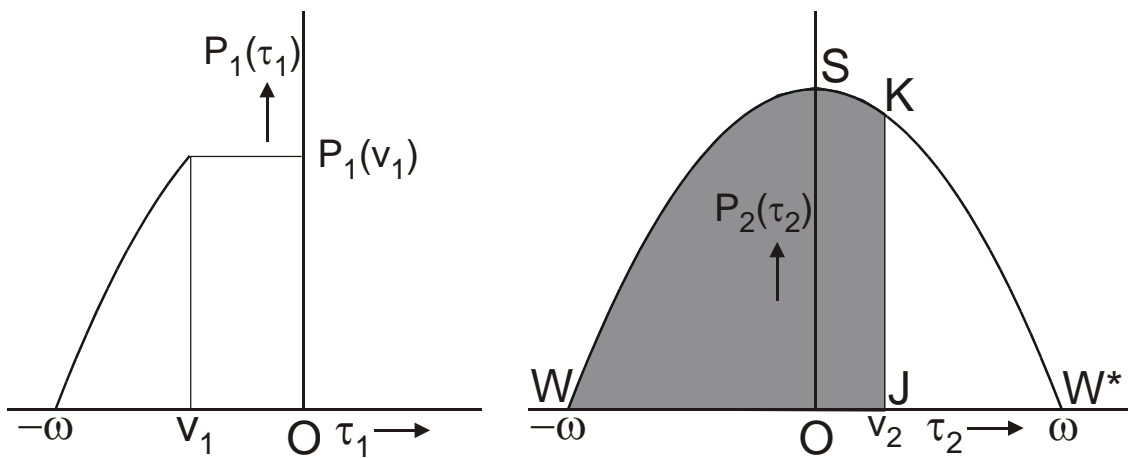
(a) The effect on $\overline{P}(\tau)$ for $v_1 - \omega < \tau < v_1 + v_2$
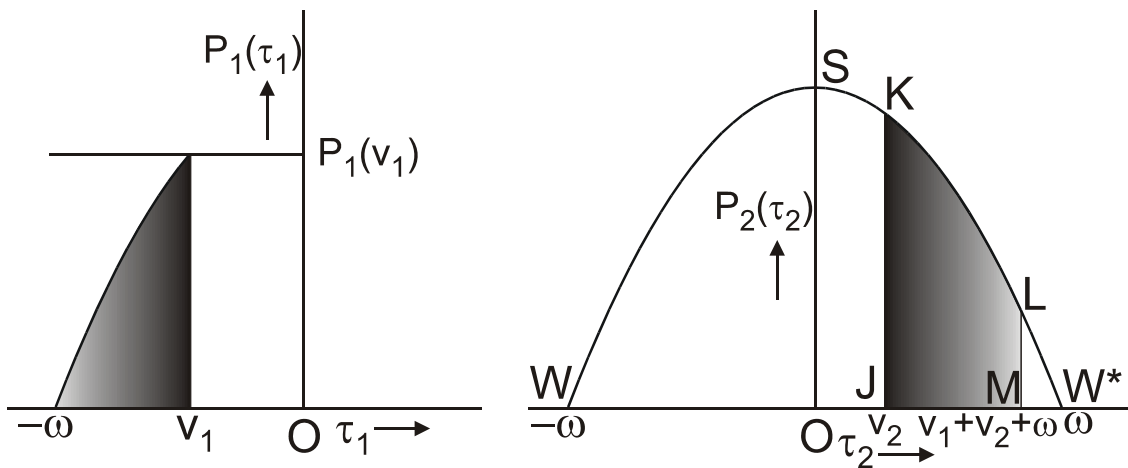
(b) Addition of $\overline{P}(v_1 + v_2)$

Figure 8. The effect of a marginal decrease in v_1 for $v_1 + v_2$ in the second interval of τ
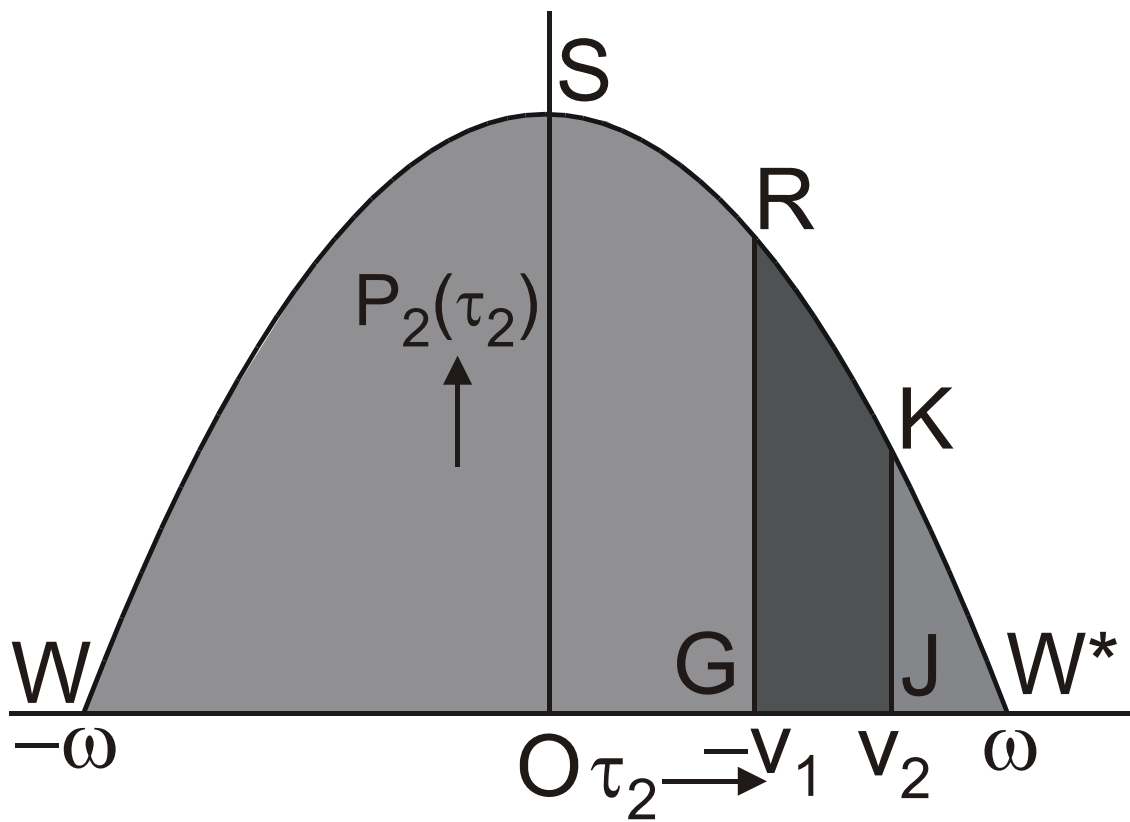
Figure 9. The effect of a marginal decrease in v_1 for $v_1 + v_2$ in the third interval of τ

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