# Group rewards and individual sanctions, applied to environmental policy[1]


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June 2008


### Abstract

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. This incentive scheme is applied in the UK Climate Change Agreements feature this incentive scheme. There is only a difference in outcome between group and individual rewards if performance is stochastic. Group rewards lead to lower effort than individual rewards if targets are realistic.



Keywords: Team incentive scheme, stochastic performance, UK Climate Change Agreements

JEL classification: D23, J33, Q58


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[1] We thank Rosie Smith and James Godber from Defra and Deborah Brzakalik from AEA Energy and Environment for providing valuable information about the CCAs. We thank Laura Castellucci, Alessio D'Amato, Andreas Lange and Franz Wirl as well as seminar participants at the Universities of Tilburg, Birmingham, Nottingham and Maryland for helpful comments. Any remaining errors are our own. Financial support from the ARC programme (grant no. D/03/20264) by the British Council and the German Academic Exchange Service (DAAD) is gratefully acknowledged. The work Dirk Rübbelke devoted to this paper is partly funded under the project "Integration of Climate and Air Quality Policies" sponsored by the Research Council of Norway and executed at the Center for International Climate and Environmental Research – Oslo.



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## 1. Introduction

Consider the following incentive scheme: A group of agents takes on a group target, which is broken down into individual targets. If the group meets its target, everyone is rewarded, whether they met their individual targets or not. If the group does not meet its target, only the agents who met their individual targets are rewarded. This group rewards/ individual sanctions scheme is applied in the UK Climate Change Agreements.

The UK government imposed a Climate Change Levy on industrial energy consumers in 2001. Energy-intensive firms could get an 80% discount on the levy if they signed a Climate Change Agreement, 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.

Potential applications of group rewards and individual sanctions extend to any organization. As long as an organization functions reasonably well, everyone is happy and there is no need to examine individual agents' contributions. However, when things go wrong, attention turns to individual performance and who is to blame.

The main purpose of our paper is to compare the equilibrium efforts under group and individual rewards (both combined with individual sanctions). This subject has not been addressed in the literature before. Equilibrium efforts are different only 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 her performance level deterministically, all agents will just meet their individual targets with individual as well as with group rewards.

However, it seems quite plausible to assume that an element of chance enters the translation from effort to performance. In environmental policy for instance, 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. In a more general setting, the problem of performance measurement error may also need to be considered.

Under certain plausible conditions, group rewards induce each agent to exert less effort than individual rewards. This is because the whole group benefits from one agent's increase in effort. This extra effort increases the probability that the group as a whole will meet the target, so that other agents who don't meet their individual target will still escape punishment. The agents are better off with group rewards when the targets remain constant. When the targets are adjusted to yield the same level of expected group performance, it is unclear which system the agents will prefer.

It may seem obvious at first sight that group rewards result in less effort than individual rewards, but actually it is not. Indeed, an example in subsection 5.3 shows that group rewards can lead to more effort. However, this can only happen for ambitious targets that have a low probability of being met. We will specify the probability function that translates effort into performance such that every effort level that can be achieved with ambitious targets can also be achieved with realistic targets. It seems plausible that a principal would prefer to set realistic targets that have a high probability of being met. With realistic targets, group rewards always lead to less effort than individual rewards.

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

## 2. Review of the literature

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). Prendergast (1999) reviews the literature. The incentive schemes that are studied are usually linear, but a step function (with a fixed bonus for exceeding a certain performance threshold) can approach the first best in some conditions: The principal must be very risk-averse and the probability of exceeding the threshold is very sensitive to the agent's action (Holmstrom, 1979; Mirrlees, 1999). Dixit (2002) argues that the government as a principal is usually very risk-averse.

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 this point. Xepapadeas (1991), Cabe and Herriges (1992) and Horan et al. (1998) refine the analysis. Where the non-point pollution literature typically 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 joint performance evaluation does worse than individual performance evaluation in a static setting, it may be preferred in a dynamic setting.

Stochastic pollution has received little attention in environmental economics. Beavis and Walker (1983ab) were the first to study this. The fine for excess emissions is usually taken to be increasing (typically linear) in the difference between actual and allowed emissions. In the present paper, as in Wirl and Noll (2007), the fine is a fixed amount. While using a different specification of the probability function for emissions, Wirl and Noll (2007) find as we do that an increase in the emission reduction target may raise as well as lower abatement. This can also occur with a fine that is proportional to the violation (Wirl and Noll, 2008).

The work that is closest to our paper is Franckx (2002, 2005), who also analyzes a group rewards/individual sanctions scheme in environmental policy, but in a different setup: An environmental agency can inspect ambient environmental quality before inspecting individual firms' compliance. If ambient environmental quality is high enough, the agency doesn't need to inspect individual firms. The crucial difference between Franckx (2002, 2005) and the present paper is that we assume costless monitoring.[3] In the UK scheme, all information on the firms' performance is available. However, the government has chosen not to consider individual firms' performance as long as their industry reaches

[3] Another difference is that Franckx' (2002, 2005) firms can only choose between complying and not complying, whereas abatement is a continuous variable for our firms.

its target. Thus, where Franckx (2002, 2005) models the game between firms and the environmental agency, we only model the game between firms.

## 3. The UK Climate Change Agreements[4]

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 were increased by 2.6%. They were subsequently to be adjusted for inflation each year.

Energy-intensive firms could obtain an 80% discount on the levy when they signed a Climate Change Agreement (CCA) with the government to reduce their energy consumption. The scheme originally covered 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 (per unit of output), but some sectors (notably steel) have absolute targets. The targets are stated in terms of improvement over the base year (usually 1998, 1999 or 2000). These targets were agreed between the government and the sectoral organisations in the months before the CCL came into force. The sectoral targets were subsequently translated into targets per firm. 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 to account for their emissions. If the 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. 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 decertified and don't receive the discount for the next two years.

All CCA firms can participate in the UK Emission Trading Scheme (UK ETS), launched in April 2002. When the CCAs were negotiated, it was envisaged that emission trading would be allowed at some point, and so the CCAs contain provisions for emission

[4] Most information in this section, unless otherwise indicated, comes from the Defra website http://www.defra.gov.uk/environment/ccl/index.htm, especially Defra (2003, 2005, 2007). See also Pearce (2006) on the CCL, de Muizon and Glachant (2004) and Glachant and de Muizon (2006) on the CCAs and Smith and Swierzbinski (2007) on the ETS.

trading. However it was still unclear at that point when emission trading would start and which form it would take.

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

When a firm overcomplies, it can notify Defra (the Department for the Environment, Food and Rural Affairs) to ringfence its 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 around £1,000 (Glachant and de Muizon, 2006). The firm then receives allowances for its ringfenced emissions.

Table 1 summarizes the emission reductions by the CCA firms in the three target periods. These are the absolute reductions from the base year. Our calculations put aggregate baseline emissions in the CCA sectors at around 90 Mton $CO_2$.[5] The steel sector, especially Corus, saw a dramatic decline in output and consequently in energy use around 2001/02. Since the steel sector has an absolute target and accounts for a quarter of energy use in the scheme, Corus might have flooded the market with allowances, removing any energy saving incentive for all other firms. Thus 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.

The start of the ETS was marked by delays in getting surplus emissions verified, causing the allowance price to rise rapidly to £12 per ton of $CO_2$ at the end of the first compliance period (September 2002). Subsequently, allowance prices settled in the £2–5 range (Smith and Swierzbinski, 2007). Table 2 summarizes market activity.

Table 3 summarizes the compliance results of the first three target periods. In some sectors, all target units were recertified, although the sector as a whole failed 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 market shares. 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

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

its target on several grounds. This adjustment, however, is only reflected in the individual, not in the sectoral target.

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” (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. In the animal feed sector “[a]ll facilities except one” (Defra, 2005) were recertified. “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 in the second milestone period, facilities were tested at the sub-sector level. Within the subsectors that failed their targets, “a number of facilities” failed to meet their individual targets and were de-certified.

For the third milestone period, Defra (2007) provides the number of facilities decertified per sector. There was one decertification each in the foundries, poultry meat processing, red meat processing, metal forming, printers and rendering sectors. There were two decertifications in the horticulture sector. The food and drink sector again failed its overall target. Three subsectors achieved their subsectoral target, but twelve did not. In the latter subsectors, fifteen facilities were decertified.

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, benefiting other firms in the sector that failed their own target. Table 2 contains our lower-bound estimate of excess reductions. For each sector that reached its target,[6] we calculated 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 their 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 target.

Ekins and Etheridge (2006) analyze the results of the 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 were very useful, because they made firms aware of the potential for energy-saving measures.

The EU Emission Trading Scheme (EU ETS) for $CO_2$ emissions, which partly overlaps the UK ETS, started on 1 January 2005. Member States could apply for their firms to opt out of the first stage of the EU ETS (2005-2007). The Commission granted an opt-out for the Direct Participants (until the scheme ended in 2006) and the CCA firms. These firms could choose between joining the EU ETS and staying in the CCA. The CCAs continued for those sectors and activities not covered by the EU ETS. There were around 500 installations covered by the EU ETS as well as by CCAs, and about 330 of these opted out of the EU ETS for the first phase (Defra, 2007). Measures were put in place to avoid double counting of emission reductions and shortfalls by firms covered by both schemes.

## 4. The model

We analyze the effort choices of agents in the same group. For simplicity, we let the group consist of two agents only. We will often refer to the UK Climate Change Agreements (CCAs), because this is the case that has inspired our model, but the group

[6] We excluded the steel sector, because as discussed above, steel firms were not allowed to sell their ringfenced emissions. Further details are available from the corresponding author upon request.

reward/individual sanction scheme could potentially be applied in many other situations. It could be applied within private as well as public organizations (e.g. for a production or a sales department) and in other areas of government policy (e.g. to incentivize hospitals to reduce waiting lists for operations).

There is a principal interested in the agents' performance. The principal has set a target for each agent's performance. The target is relative to some benchmark, for instance previous performance or expected performance without the incentive scheme. Benchmark performance is normalized to zero. Agent $j$, $j = 1, 2$, has a target $T_j > 0$ for improvement of her performance. The group target $T$ is the sum of individual targets: $T = T_1 + T_2$.

Agent $j$ undertakes an effort $e_j$ to improve her performance $m_j$. Her cost of effort is given by $C_j(e_j)$, with:

$$C_j^{'}(0) = 0, \qquad C_j^{'} > 0 \quad for\ e_j > 0, \qquad C_j^{''} > 0 \quad for\ e_j \geq 0 \qquad (1)$$

The cost of effort $C_j(e_j)$ is measured in units commensurate with money. Effort $e_j$ itself is measured in the same units as performance improvement $m_j$. The principal can observe an agent's performance, but not her effort.

The sanction for not reaching the target level of performance improvement is a fixed fine $f$, irrespective of the actual performance. 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.

Let us first examine the case of deterministic performance, where firm $j$'s performance improvement $m_j$ is completely determined by her effort $e_j$: $m_j = e_j$. With individual rewards, agent $j$ sets her effort $e_j$ equal to the target $T_j$ if she decides to comply. Her costs of compliance are thus $C_j(T_j)$. If she chooses not comply, she will not make any effort and pay the fine $f$. We assume that $C_j(T_j) < f$, thus the agent decides to comply and sets $e_j = T_j$.

With group rewards, the group target is $T = T_1 + T_2$. Agent $j$ is only fined if both $e_j < T_j$ and $e_1 + e_2 < T$. Agent $j$'s reaction function is then $e_j = min\ (T_j, T - e_i)$ for $j = 1,2$. The unique Nash equilibrium is $e_j = T_j$, $j = 1,2$. Thus with deterministic performance, agents respond in the same way to individual and group rewards.

With stochastic performance, the agents' performance is affected by random and uncorrelated shocks. Agent $j$ can only affect the expected level (or more precisely, the probability distribution) of her performance through $e_j$.

Applying this assumption to our environmental policy example, there are of course several reasons why emission shocks may be correlated, either positively[7] 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 agent *j*'s performance improvement $m_j$ satisfies:[8]

**Assumption 1.** With stochastic performance, the difference between agent *j*'s performance improvement $m_j$ and her effort $e_j$ is described by the continuously differentiable probability function $P_j(m_j-e_j)$ with support $[-\omega_j,\eta_j]$, $\omega_j > 0$, $\eta_j \geq 0$, $\lim_{x\downarrow-\omega} P_j(x) = 0,$ and the first and highest mode at zero, i.e. $P_j(0) \geq P_j(m_j-e_j)$ for all $m_j-e_j \in [-\omega_j,\eta_j]$ and $P_j'(m_j-e_j) > 0$ for all $m_j-e_j \in (-\omega_j,0)$.

These conditions imply that the probability function of performance improvement $m_j$ is increasing for the lowest values of $m_j$. It may be increasing throughout, or have one or more modes (peaks) in the interior, as long as the first peak is the highest. For ease of notation, we set $m_j$ at the lowest mode equal to the agent's effort $e_j$. An increase in effort moves the probability distribution to the right, without changing its shape.[9]

The corresponding distribution function is $D_j(m_j-e_j)$, so that $D_j(T_j-e_j) = \Pr(m_j < T_j\,|e_j)$ is the probability that agent *j*'s performance improvement is below her individual target $T_j$, given her effort $e_j$.

The UK CCAs that inspired this model also contain an Emission Trading Scheme (ETS, Section 3). For simplicity, we will disregard this scheme. We also note that when the CCAs were agreed, it was unclear when and how emission trading would be introduced.

[7] Positively correlated shocks make relative performance evaluation more attractive (Holmstrom, 1982).

[8] This assumption describes the most general probability function for which we can derive our main result (Proposition 1). It does not include the uniform distribution, which would be the simplest function to analyze. With the uniform distribution, an agent's effort (if positive) under individual rewards would not depend on the target ($MB_j^1$ in Figure 1 would be horizontal). Group rewards would lead to lower effort than individual rewards for relatively lenient targets and to the same effort level for relatively strict targets.

In the end, the ETS started in April 2002, halfway through the first compliance period (Oct 2001–Sep 2002). As we saw in Section 3, delays in verification of surplus emissions led to an increase in the allowance price to £12 by September 2002. We can also point to the high cost of verification of ringfenced emissions (£1,000, see Section 3). 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. It appears that at least in the first target period, many firms did not ringfence their emission reductions. Our lower-bound estimate of excess emission reduction in period 1 is 3.2 Mton, a large amount compared to 3.8 Mton ringfenced (Table 2). Finally, note that between 5 and 12% of the firms in each period were not recertified (Table 3). Thus a substantial number of firms did not only fail to reach their target outright, but also chose not to make up for it by buying allowances.

Under incentive scheme *ρ,* with *ρ* either equal to *I* (individual rewards) or *G* (group rewards), the risk-neutral agent *j* minimizes total cost $TC_j^\rho$:

$$TC_j^\rho = \pi_j^\rho(e_1, e_2) f + C_j(e_j) \qquad (2)$$

where $\pi_j^\rho$ is the probability that agent *j* will be fined under incentive scheme *ρ*.

We assume that the principal is more concerned about the agents' fine probability than about his own revenues from the scheme. If there are two target values that result in the same level of effort, the principal will set the lowest target value, which yields the lowest fine probability. The principal may care altruistically about the agents' fine probability or, more likely, because he needs the agents' goodwill for their continued participation in the scheme. In addition, failure to reach the targets may reflect badly upon the principal.

## 5. Stochastic performance

### 5.1 Individual rewards

With individual rewards *I*, agent *j* is fined if and only if her performance improvement $m_j$ is below her individual target $T_j$. When the agent's effort is $e_j$, the probability that this happens is $D_j(T_j - e_j)$. Substituting this into (2), we see that the agent minimizes:

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[9] This is a common assumption in the stochastic emissions literature, e.g. Beavis and Dobbs (1987), Mrozek and Keeler (2004).

$$TC_j^I(e_j) = D_j(T_j - e_j)f + C_j(e_j) \quad (3)$$

The first order condition is:

$$P_j(T_j - a_j)f = C_j^{'}(a_j) \quad (4)$$

The second order condition is:

$$P_j^{'}(T_j - e_j)f + C_j^{''}(e_j) > 0 \quad (5)$$

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 $e_j^I$ that solves (3).

The effect of an increase in the target level of performance improvement is, from (4):

$$\frac{de_j^I}{dT_j} = \frac{P_j^{'}\left(T_j - e_j^I\right)f}{P_j^{'}\left(T_j - e_j^I\right) + C_j^{''}\left(e_j^I\right)} \quad (6)$$

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

Let us illustrate this point using specific functional forms. All figures in this paper were derived and drawn assuming (where applicable) that the two agents' probability and cost functions are identical and quadratic, and their targets are identical. Our formal analysis is not limited to these cases, however.

The general form of the quadratic probability function is:

$$P_j(m_j - e_j) = \begin{cases} 0 & \text{for } m_j - e_j < \frac{3}{4\theta_j},\ m_j - e_j > \frac{3}{4\theta_j} \\ \theta_j - \frac{16}{9}\theta_j^3\left(m_j - e_j\right)^2 & \text{for } m_j - e_j \in \left[-\frac{3}{4\theta_j}, \frac{3}{4\theta_j}\right] \end{cases} \quad (7)$$

With quadratic cost of effort:

$$C_j(e_j) = \frac{1}{2}c_j e_j^2 \quad (8)$$

first order condition (4) for cost minimization under individual rewards becomes:

$$\left[\theta_j - \frac{16}{9}\theta_j^3(T_j - e_j)^2\right]f = c_j e_j \quad (9)$$

The $MB_j^I$ curve in Figure 1 shows agent $j$'s marginal benefits of effort, given by the LHS of (4) and (9). The $MC_j$ curve shows her marginal cost of effort, given by the RHS of (4) and (9).

Solving (9) for $e_j^I$ yields:

$$e_j^{\ I} = T_j + \frac{-9 + 3\sqrt{9 + 64\theta_j^4\phi_j^2 - 64\theta_j^3\phi_j T_j}}{32\theta_j^3\phi_j} \tag{10}$$

with $\phi_j \equiv f / c_j$. Totally differentiating (1) with respect to $T_j$ yields:

$$\frac{de_j^{\ I}}{dT_j} = 1 - \frac{3}{\sqrt{9 + 64\theta_j^4\phi_j^2 - 64\theta_j^3\phi_j T_j}} = \frac{\left(e_j^{\ I} - T_j\right)32\theta_j^3\phi_j}{3\sqrt{9 + 64\theta_j^4\phi_j^2 - 64\theta_j^3\phi_j T_j}} \tag{11}$$

The second equality follows from (10). This shows, as equation (6) did, that $e_j^I$ is increasing (decreasing) in $T_j$ for $e_j^I$ above (below) $T_j$. This is illustrated in Figure 1.[10] Figure 1a shows the case where effort exceeds the target, so that the probability function is increasing. Then an increase in the target from $T_j$ to $T_j$' results in an increase in effort from $e_j^I$ to $e_j^{I}$'. In Figure 1b effort is below the target, and the probability function is decreasing. Now an increase in the target from $T_j$ to $T_j$' results in a decrease in effort from $e_j^I$ to $e_j^{\ I}$'.

Figure 2 shows the agent's choice of effort as a function $e_j^I(T_j)$ of the target (equation (10)). When the target is relatively low, effort exceeds the target (the $e_j^I(T_j)$ curve is above the $e_j = T_j$ line). Then, as we know from (6) and (11), effort is increasing in the target. Effort is highest for $e_j = \bar{e}_j = \bar{T}_j$. We will call targets below $\bar{T}_j$ realistic and targets above $\bar{T}_j$ ambitious. For ambitious targets, effort is decreasing in the target. When the target is stricter than $T_j^*$, the agent prefers not to make any effort and to incur the fine with certainty. All effort levels between $e_j^*$ and $\bar{e}_j$ that can be achieved by ambitious targets can also be achieved by realistic targets. For instance, effort level $e_j$' can be achieved with realistic target $T_j^r$ and ambitious target $T_j^a$.

Since the probability function may have several modes, effort could be increasing in the target for targets above $\bar{T}_j$. However, under Assumption 1 that the first peak is the

[10] Since from (4), $dMB_j/de_j = -P_j'(T_j - e_j)f$, $P_j'(T_j - e_j) > 0$ implies decreasing $MB_j$ in Figure 1. When the $MC_j$ curve intersects the $MB_j^I$ curve twice, the first point of intersection is a cost maximum.

highest, effort cannot exceed $\bar{e}_j$. Thus it is a general result that all effort levels that can be achieved with ambitious targets can also be achieved by realistic targets. As explained at the end of Section 4, we assume the principal will always set the targets in the realistic range. Thus we have:

**Lemma 1.** With individual rewards, agent *j*'s effort exceeds her target, so that $P_j'(T_j - e_j^I) > 0$, i.e. the probability function is upward sloping.

It seems that the targets of the UK CCAs 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 between 5 and 12% of firms were sanctioned for their (and their industry's) failing to meet the target in each milestone period (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 where an agent is only sanctioned if both she misses her own target and her group misses its target. Without loss of generality, we focus on agent 1. The probability that she is fined under group rewards *G* is:

$$\pi_1^G = \Pr(m_1 < T_1)\Pr(m_1 + m_2 < T \mid m_1 < T_1) \tag{12}$$

i.e. the probability that her own performance improvement $m_1$ is below her individual target $T_1$ multiplied by the probability that the group's improvement $m_1 + m_2$ is below its target $T = T_1 + T_2$, given that $m_1 < T_1$.

Define:

$$v_j \equiv T_j - e_j \qquad \tau_j \equiv m_j - e_j \qquad \tau \equiv \tau_1 + \tau_2 \tag{13}$$

By Lemma 1, $v_j < 0$ with individual rewards. In case agent 1 misses her target, $\tau_1$ is in the range $[-\omega_1, v_1]$ while $\tau_2$ can still be anywhere in the whole range $[-\omega_2, \eta_2]$. Substituting (13) into (12), we can write agent 1's fine probability as:

$$\pi_1^G(v_1, v_2) = \Pr(\tau_1 < v_1)\Pr(\tau < v_1 + v_2 \mid \tau_1 < v_1) \tag{14}$$

We can also write the probability as:

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

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

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

where $P(\tau)$ is the probability function for $\tau = \tau_1 + \tau_2$ with $\tau_1 \in [-\omega_1, v_1]$ and $\tau_2 \in [-\omega_2, \eta_2]$. Figure 3 illustrates how to derive this scaled probability function for two agents with identical symmetric probability functions, so that $\omega_1 = \omega_2 = \eta_2 = \omega$. For agent 2 we need the probability function over the whole range $\tau_2 \in [-\omega, \omega]$, as shown on the right of Figures 3a–c. For agent 1 we use the probability function over the range $\tau_1 \in [-\omega, v_1]$ given that $\tau_1 < v_1$, but by (14) 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 3a–c.

Figure 3a shows how to determine the probability density at a $\tau^*$ between $-2\omega$ and $v_1 - \omega$. When $\tau_1$ is at its lowest possible value of $-\omega$, it has to be combined with $\tau_2 = \tau^* + \omega$ to achieve $\tau^*$. A slightly higher value for $\tau_1$ also gives $\tau^*$ when combined with an equally slightly lower value for $\tau_2$. We can keep on increasing $\tau_1$ and decreasing $\tau_2$ until we come to $\tau_2 = -\omega$, which needs to be paired with $\tau_1 = \tau^* + \omega$ to achieve $\tau^*$. Thus as we let $\tau_1$ increase from $-\omega$ to $\tau^* + \omega$ (from light to dark in Figure 3a), the corresponding values for $\tau_2$ decrease from $\tau^* + \omega$ to $-\omega$ (again from light to dark). For each pair of $\tau_1$ and $\tau_2$ 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:

$$\overline{P}(\tau^*, v_1) = \int_{-\omega}^{\tau^*+\omega} P_1(z)P_2(\tau - z)dz \qquad for \quad -2\omega < \tau^* < v_1 - \omega \tag{15}$$

Figure 3b shows how to determine the probability density at a $\tau'$ between $v_1 - \omega$ and 0. This $\tau'$ can be achieved with any value of $\tau_1$ between $-\omega$ and $v_1$. The maximum $\tau_1$ value of $v_1$ has to be paired with $\tau_2 = \tau' - v_1$, while the minimum $\tau_1$ value of $-\omega$ is paired with $\tau_2 = \tau' + \omega$. This procedure works as long $\tau' + \omega$ is below the maximum $\tau_2$ value of $\omega$. We have thus found that:

$$\overline{P}(\tau', v_1) = \int_{-\omega}^{v_1} P_1(z)P_2(\tau' - z)dz \qquad for \quad v_1 - \omega < \tau' < 0 \tag{16}$$

Figure 3c shows how to determine the probability density at a $\tau$" between 0 and $v_1 + \omega$. Now $\tau$" is so high that it cannot be obtained with the lowest values of $\tau_1$ anymore. The maximum value of $\tau_2$ is $\omega$, which has to be paired with $\tau'' - \omega > -\omega$ to obtain $\tau$". As before, the maximum $\tau_1$ value of $v_1$ has to be paired with $\tau_2 = \tau'' - v_1$. Thus we have:

$$\overline{P}(\tau'', v_1) = \int_{\tau-\omega}^{v_1} P_1(z)P_2(\tau - z)dz \quad for \quad 0 < \tau'' < v_1 + \omega \tag{17}$$

Let us now generalize (15) to (17) 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 performance improvements is smaller for agent 1 than for agent 2, given that agent 1 misses her 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:

$$\overline{P}(\tau, v_1) = \begin{cases} \int_{-\omega_1}^{\tau+\omega_2} P_1(z)P_2(\tau - z)dz & for \quad -\omega_1 - \omega_2 < \tau < v_1 - \omega_2 \\ \int_{-\omega_1}^{v_1} P_1(z)P_2(\tau - z)dz & for \quad v_1 - \omega_2 < \tau < \eta_2 - \omega_1 \\ \int_{\tau-\eta_2}^{v_1} P_1(z)P_2(\tau - z)dz & for \quad \eta_2 - \omega_1 < \tau < v_1 + \eta_2 \end{cases} \tag{18}$$

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

$$\overline{P}(\tau, v_1) = \begin{cases} \int_{-\omega_1}^{\tau+\omega_2} P_1(z)P_2(\tau - z)dz & for \quad -\omega_1 - \omega_2 < \tau < \eta_2 - \omega_1 \\ \int_{\tau-\eta_2}^{\tau+\omega_2} P_1(z)P_2(\tau - z)dz & for \quad \eta_2 - \omega_1 < \tau < v_1 - \omega_2 \\ \int_{\tau-\eta_2}^{v_1} P_1(z)P_2(\tau - z)dz & for \quad v_1 - \omega_2 < \tau < v_1 + \eta_2 \end{cases} \tag{19}$$

Agent 1's first order condition for cost minimization is then, from (2) and (9):

$$\frac{\partial \pi_1^G(v_1, v_2)}{\partial v_1} f = f \frac{\partial}{\partial v_1} \int_{-\omega_1-\omega_2}^{v_1+v_2} \overline{P}(\tau, v_1) d\tau = C'(a_1) \tag{20}$$

with $\overline{P}(\tau, v_1)$ given by (18) or (19).

### 5.3 Comparing individual and group rewards

We will now examine whether group rewards lead to less effort than individual rewards. We then compare the agent's payoffs under the two schemes.

Under individual as well as group rewards, as shown by (4) and (20) respectively, agent 1 sets her marginal benefits of effort equal to her marginal cost. Since marginal cost is increasing in effort, lower marginal benefits of effort under group rewards would translate in lower equilibrium effort:

**Lemma 2.** If the sensitivity of agent 1's fine probability $\pi_1^\rho$ to her effort $e_1$ is lower with group rewards $G$ than with individual rewards $I$, she will exert less effort with group rewards. That is, $e_1^G < e_1^I$ if:

$$\left|\frac{\partial \pi_1^G(e_1, e_2)}{\partial e_1}\right| < \left|\frac{\partial \pi_1^I(e_1)}{\partial e_1}\right| \qquad \textit{for all } e_1 \in [T_1, T_1 + \omega_1] \tag{21}$$

It may seem at first sight that effort should always be lower with group rewards and therefore (21) should always hold. The argument would be that group rewards make effort a public good and an agent tries to free ride on the other agent's effort. However, differentiating agent 1's fine probability in (14) with respect to $v_1$ shows that the analysis is not that straightforward:

$$\frac{\partial \pi_1^G(v_1, v_2)}{\partial v_1} = P_1(v_1)\Pr(\tau < v_1 + v_2 \mid \tau_1 < v_1) + \Pr(\tau_1 < v_1)\frac{\partial \Pr(\tau < v_1 + v_2 \mid \tau_1 < v_1)}{\partial v_1} \tag{22}$$

The first term on the RHS denotes the change in agent 1's probability of missing her individual target, multiplied by the probability that the group misses its target. With individual targets, all that matters is the former [$P_1(v_1)$], and the first term on the RHS is obviously smaller than $P_1(v_1)$. However, we must also take the second term on the RHS of (22) into account. This is the probability that agent 1 misses the target, multiplied by the change in the probability that the group misses its target, given that agent 1 has missed hers. This term is positive, which makes it ambiguous whether the RHS of (22) is larger or smaller than $P_1(v_1)$.

We will now show that the RHS of (22) is smaller than $P_1(v_1)$ and thus (21) holds when the target is realistic as defined in subsection 5.1, so that Lemma 1 applies. We will then present the solution for individual and group rewards with quadratic cost and probability functions. We will see that with ambitious targets, inequality (21) may not hold, so that effort with group rewards can be higher than with individual rewards.

Let us concentrate on the case where the two agents have identical symmetric probability functions for their performance, so that $\omega_1 = \omega_2 = \eta_2 = \omega$.[11] If agent 2 exerts so little effort under group rewards that he will certainly fail his individual target ($v_2 > \omega$), then for agent 1 there is no difference between individual and group rewards. Agent 1's effort will be the same under both schemes, which is not a very interesting case. Thus we assume $v_2 < \omega$. There is no point for agent 2 to make an effort beyond the point where he will reach his individual target for certain. Thus $v_2 > -\omega$. Then by (18) and (19), $v_1 + v_2$ is either in the second or the third interval of $\tau$.

Let us first examine the case with $v_1 + v_2$ in the second interval. We illustrated in Figure 3a how to calculate the scaled probability function $\overline{P}(\tau)$ in the first interval of $\tau$ between $-2\omega$ 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 3b illustrated how to calculate $\overline{P}(\tau)$ in the second interval of $\tau$ 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 $\tau$ 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 $\tau$, we lose $P_1(v_1)$ multiplied by $P_2(\tau - v_1)$. Figure 4a illustrates how to calculate this loss. The lowest $\tau$ value of $v_1 - \omega$ is achieved with $\tau_1 = v_1$ plus $\tau_2 = -\omega$. The highest $\tau$ 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 4b illustrates how to find this $\overline{P}(v_1 + v_2)$. Analogously to Figure 3b, the minimum $\tau_1$ value of $-\omega$ results in $v_1 + v_2$ when combined with the $\tau_2$ value of $v_1 + v_2 + \omega$. The maximum $\tau_1$ 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 agent 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 4.

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

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 effort on the fine probability with group rewards is thus less than $P_1(v_1)$, which is the effect 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. Again, for every τ in the second interval, we lose $P_1(v_1)$ times $P_2(\tau - v_1)$. The lowest $\tau$ value of $v_1 - \omega$ is again achieved with $\tau_1 = v_1$ plus $\tau_2 = -\omega$. The highest $\tau$ value is now 0, which is achieved with $\tau_1 = v_1$ plus $\tau_2 = -v_1$. The loss is then $P_1(v_1)$ times the area *WSRG* in Figure 5 under the $P_2(v_2)$ curve from $-\omega$ to $-v_1$.

There are two changes in the third interval of τ. First, for every $\tau$ in the interior we lose $P_1(v_1)$ multiplied by $P_2(\tau - v_1)$. The lowest $\tau$ value of 0 is achieved with $\tau_1 = v_1$ plus $\tau_2 = -v_1$. The highest $\tau$ 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 5 under the $P_2(v_2)$ curve from $-v_1$ to $v_2$.

The other change in the third interval is a marginal decrease in the critical τ value from $v_1 + v_2$, so that we lose $\overline{P}(v_1 + v_2)$. Analogously to Figure 3c, the maximum $\tau_1$ value of $v_1$ is combined with $\tau_2 = v_2$ to yield $v_1 + v_2$. The maximum $\tau_2$ value of $\omega$ results in $v_1 + v_2$ when combined with the $\tau_1$ value of $v_1 + v_2 - \omega$. As the $P_1(\tau_1)$ curve is rising in $[v_1+v_2-\omega, v_1]$, 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 $\omega$.

The decrease in agent 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 effort on the fine probability is less with group rewards than with individual rewards.

Formally, we can show:[12]

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

[12] The proof is in the Appendix.

Having sketched the proof of this proposition for a quadratic probability function, let us now present the solution for this case with group rewards, combined with a quadratic effort cost function, as we did in subsection 5.1 for individual rewards.[13]

To simplify the analysis, let us set $\theta_1 = \theta_2 = 1$ in (7) and $c_1 = c_2 = c$ in (8) so that $e_1^G = e_2^G$ in the Nash equilibrium. Now (18) becomes:

$$\overline{P}(\tau, v_1) = \begin{cases} \int_{-3/4}^{\tau+3/4} P_1(z)P_2(\tau - z)dz & for \quad -3/2 < \tau < v_1 - 3/4 \\ \int_{-3/4}^{v_1} P_1(z)P_2(\tau - z)dz & for \quad v_1 - 3/4 < \tau < 0 \\ \int_{\tau-3/4}^{v_1} P_1(z)P_2(\tau - z)dz & for \quad 0 < \tau < v_1 + 3/4 \end{cases}$$

When $v_1 + v_2 < 0$, it can be shown that differentiating the fine probability with respect to $v_1$ and subsequently setting $v_2 = v_1$ yields:

$$\left. \frac{\partial}{\partial v_1} \int_{-3/2}^{v_1+v_2} \overline{P}(\tau, v_1) d\tau \right|_{v_2=v_1<0} = \frac{(3+4v_1)^3(104v_1^2 + 234v_1 + 81)}{2430} \tag{23}$$

The same procedure for $v_1 + v_2 > 0$ yields:

$$\left. \frac{\partial}{\partial v_1} \int_{-3/2}^{v_1+v_2} \overline{P}(\tau, v_1) d\tau \right|_{v_2=v_1>0} = \frac{(3-4v_1)(128v_1^4 + 96v_1^3 - 408v_1^2 + 594v_1 + 243)}{810} \tag{24}$$

Figure 6 shows agent 1's equilibrium marginal benefits $\overline{MB_1^G}$, given that $e_2^G = e_1^G$, for the case $T_1 = T_2 = 0.7, f = 1$. The curve is described by (24) in the interval [0; 0.7] and by (23) in the interval [0.7; 1.45]. We see that agent 1's marginal benefits are lower under group rewards than under individual rewards (the $MB_1^I$ curve) for all $e_1$ above the target of 0.7, but they are higher for some $e_1$ below 0.7. Figure 6 features two marginal cost curves, one of which (*MC**) results in less effort with group rewards and the other (*MC***) in higher effort. With the *MC** curve $C' = e_1/4$, effort is 1.31 with individual and 1.07 with group rewards. With the *MC*** curve $C' = 2e_1$, effort is 0.44 with individual and 0.46 with group rewards.

However, following the argument from the end of Section 4, if the principal wants to achieve an effort of 0.44 with individual rewards, there is no need to set the target as high as 0.7. Using (10), we see that a target of 0.18 also results in effort of 0.44, coupled with a much higher probability of achieving the target.

[13] Further details are available from the corresponding author upon request.

Returning to the general case, let us compare an agent's total cost under individual and group rewards. When the targets are the same under both regimes, we can write:

$$TC_1^I\left(e_1^I\right) = D_1(T_1 - e_1^I)f + C_1(e_1^I) >$$
$$> D_1(T_1 - e_1^I)\Pr\left(m_1^I + m_2^G < T \mid m_1^I < T_1\right)f + C_1\left(e_1^I\right) > \pi_1^G f + C_1\left(e_1^G\right) = TC_1^G\left(e_1^G, e_2^G\right)$$

The first inequality follows from $Pr(m_1^I + m_2^G < T \mid m_1^I < T_1) < 1$ and the second one from the fact that $e_1^G$ minimizes agent 1's total cost with group rewards, given $e_2^G$.[14]

When the principal realizes that group rewards lead to less effort than individual rewards, he may wish to set stricter targets under group rewards. Then it is unclear which system the agents would prefer. On the one hand, the probability that an agent misses her individual target is now higher under group rewards. On the other hand, even if the agent misses her individual target, she 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 agents' actions determine their performance exactly, there is no difference between the two systems. There is a difference when performance is stochastic. An agent will exert less effort under group rewards than under individual rewards if the principal sets a realistic target. Group rewards can be seen as a sort of group insurance scheme against fines for underperformance.

When group rewards lead to less effort than individual rewards, one might wonder why a 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

[14] Note that both inequalities also hold if effort is higher under group rewards.

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 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 performance is stochastic, individual rewards can be regarded as unfair. Two identical agents can exert exactly the same effort, yet one is punished for underperformance while the other reaches her performance target and is rewarded. Reward or punishment is down to luck. The group reward scheme is fairer, because one agent's accidental underachievement can be compensated by another agent's accidental overachievement. The probability that one agent is punished while the other is not is lower with group rewards.

The second advantage of group rewards is that there is something in it for everyone, for the principal as well as for the agents. The principal can point to a set of targets that look quite ambitious. However, the agents know that even if they don't meet their individual target, they may still escape the fine.

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**Appendix. Proof of Proposition 1**

Without loss of generality, let us consider agent 1. By Lemma 2 and using (4) and (13), agent 1's effort under group rewards is lower than under individual rewards if and only if:

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

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

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 (18). Then from (18) and (20):

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

For the first term on the RHS of (A.2) we find from (21):

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

For the second term on the RHS of (A.2) we find from (21):

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

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 (21). Then from (21) and (20):

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

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 (21), 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 (19). Then from (19) and (20):

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

The first term on the RHS can be rewritten as:

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

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

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

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.

## Tables

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

| | Actual | Target | Actual minus target |
|---|---|---|---|
| Target Period 1 | 16.4 | 6.0 (12.3) | 10.4 (4.1) |
| Target Period 2 | 14.4 | 5.5 (9.3) | 8.9 (5.1) |
| Target Period 3 | 16.4 | 9.1 (12.3) | 7.3 (4.1) |

Source: Defra (2007)

Table 2. Emissions trading by CCA firms

| | No. target units making retirements | Allowances retired* | Allowances ringfenced* | Allowances verified for sales* | Excess emission reduction*,** |
|---|---|---|---|---|---|
| TP1 | 1,026 | 0.578 | 3.8 | 0.6 | 3.2 |
| TP2 | 1,137 | 0.905 | 6.0 | 0.6 | 0.23 |
| TP3 | 1,454 | 2.600 | 3.9 | 0.4 | 1.7 |

TP = Target Period *in million $tCO_2$ **lower-bound estimate

Source: Defra (2007), own calculations

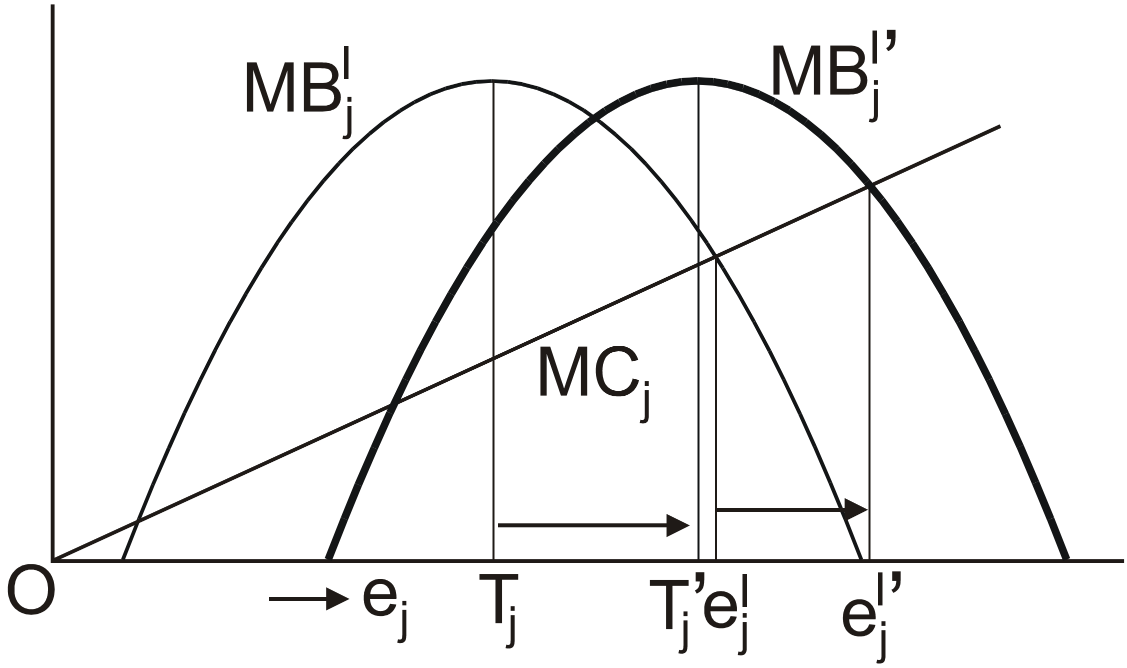
Table 3. UK CCAs: Compliance results from the first three milestone periods

| | 2002 | 2004 | 2006 |
|---|---|---|---|
| Number of sectors with: | | | |
| • Sectoral target met | 24 | 19 | 33 |
| • All firms recertified | 35 | 41 | 42 |
| • Not all firms recertified | 11 | 5 | 8 |
| Number of target units: | | | |
| • Recertified | 5,042 (88%) | 4,420 (95%) | 4,401 (92%) |
| • Not recertified | 219 | 23 | 23 |
| • Left the agreement | 164 | 228 | 345 |
| • Did not submit data | 317 | 4 | 116 |

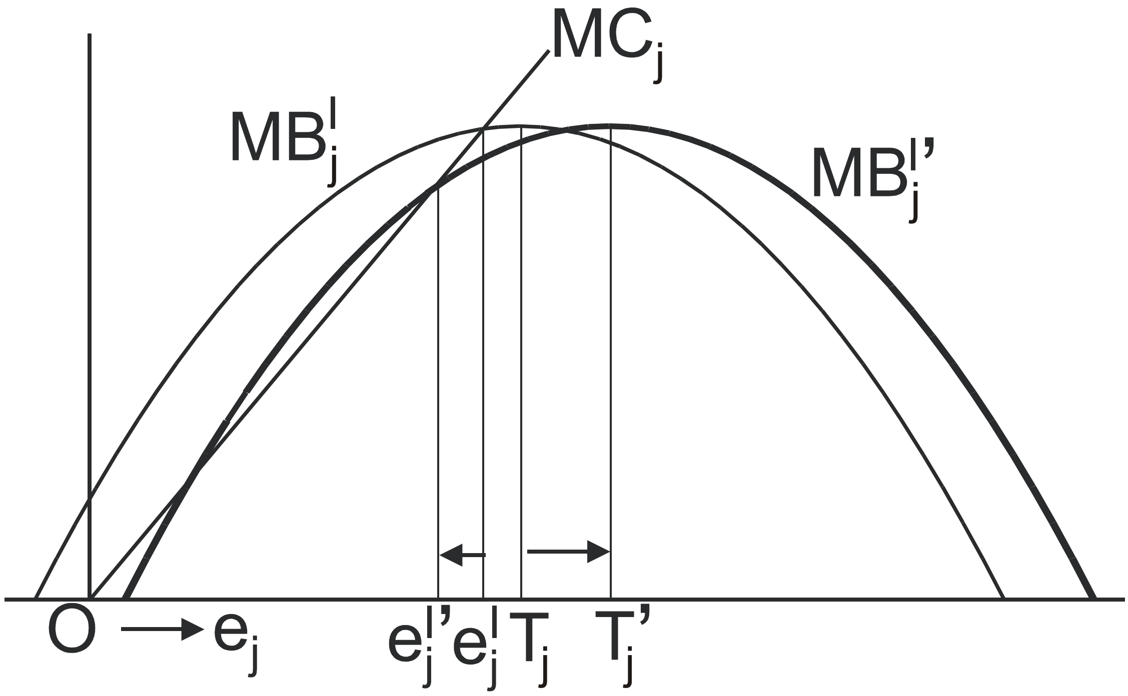
Note: Five subsectors of ceramics (with no sectoral target) treated as sectors

Source: Compiled from Defra (2003, 2005, 2007)

**Figures**




(a) Effort above target




(b) Effort below target

Figure 1. The effect of a change in agent *j*'s target $T_j$ on her effort $e_j^I$ under individual rewards

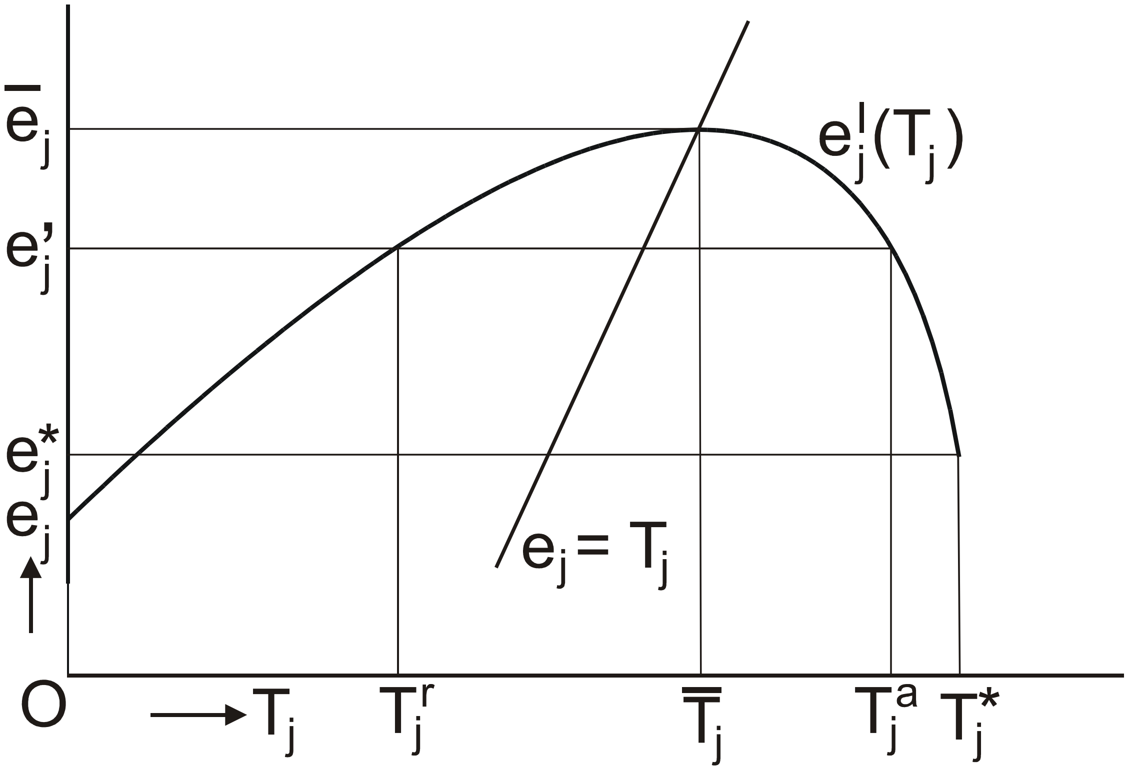
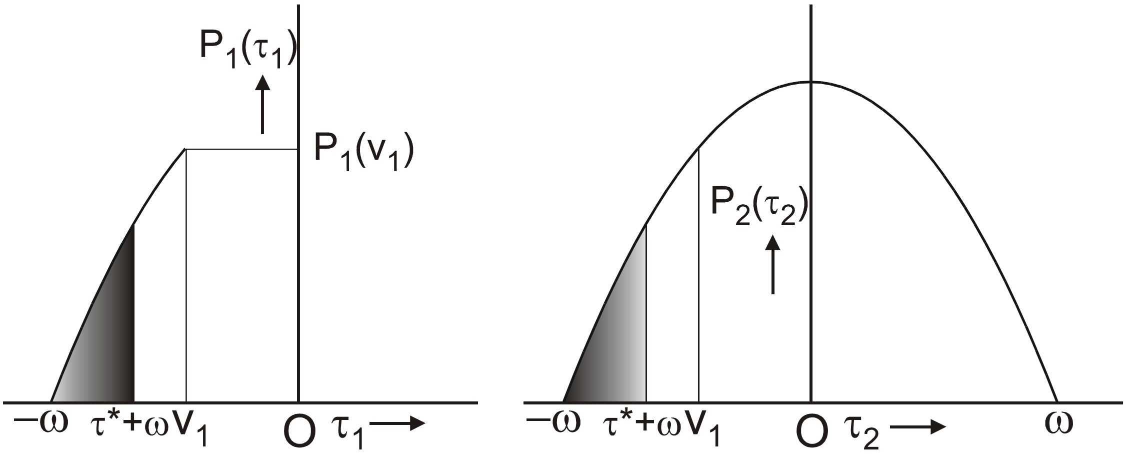
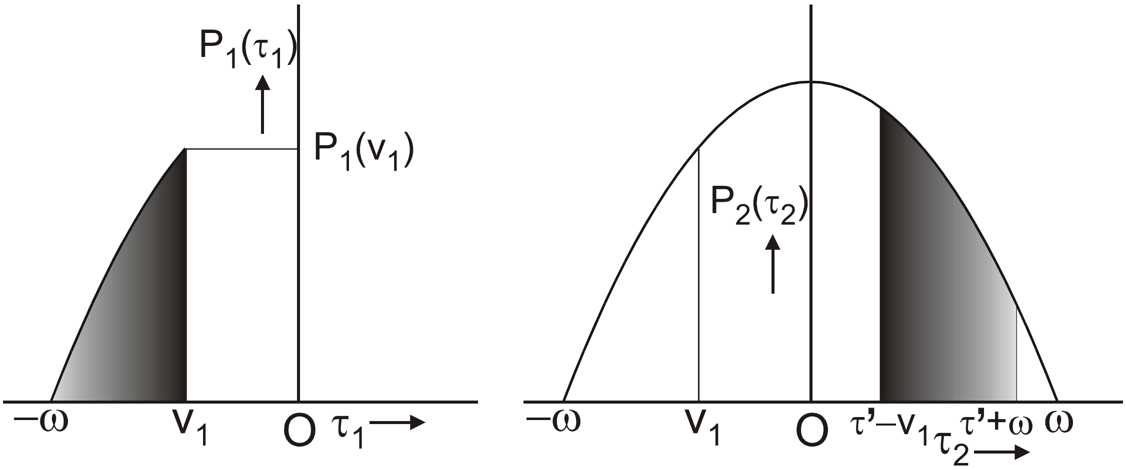


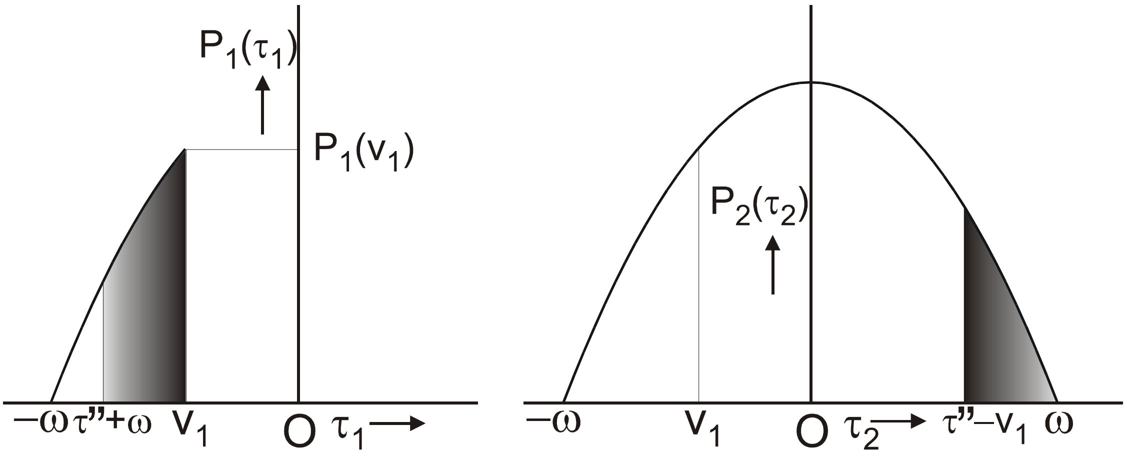

Figure 2. Agent *j*'s effort $e_j^I$ under individual rewards as a function of the target $T_j$




(a) $\overline{P}(\tau^*)$ with $-2\omega < \tau^* < v_1 - \omega$

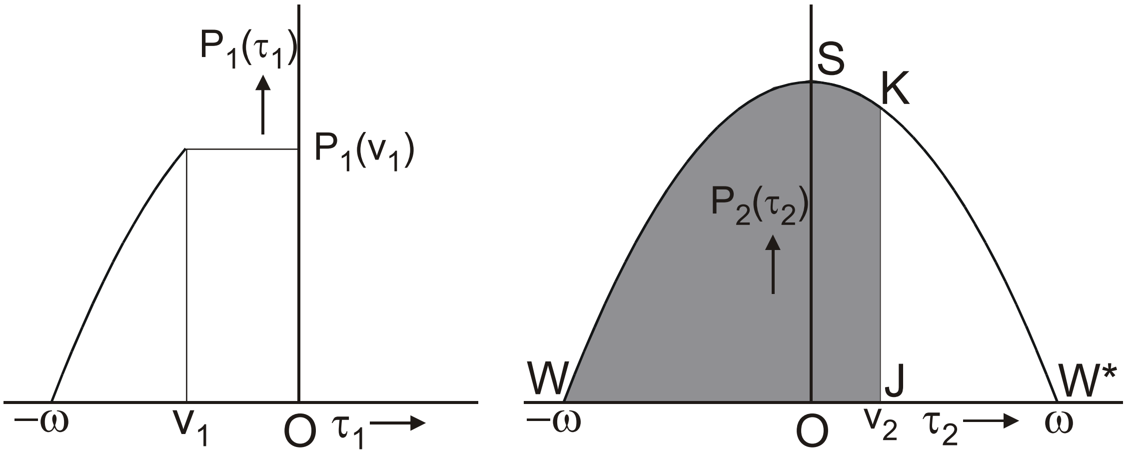



(b) $\overline{P}(\tau')$ with $v_1 - \omega < \tau' < 0$

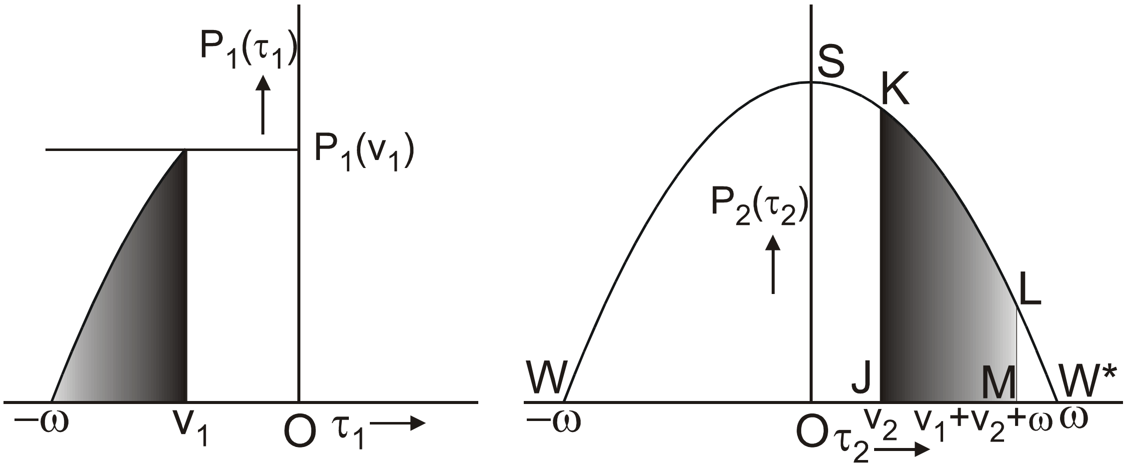



(c) $\overline{P}(\tau'')$ with $0 < \tau'' < v_1 + \omega$

Figure 3. Deriving the scaled probability function $\overline{P}(\tau)$ of $\tau = \tau_1 + \tau_2$




(a) The effect on $\overline{P}(\tau)$ for $v_1 - \omega < \tau < v_1 + v_2$




(b) Loss of $\overline{P}(v_1 + v_2)$

Figure 4. The effect of a marginal decrease in $v_1$ for $v_1 + v_2$ in the second interval of $\tau$

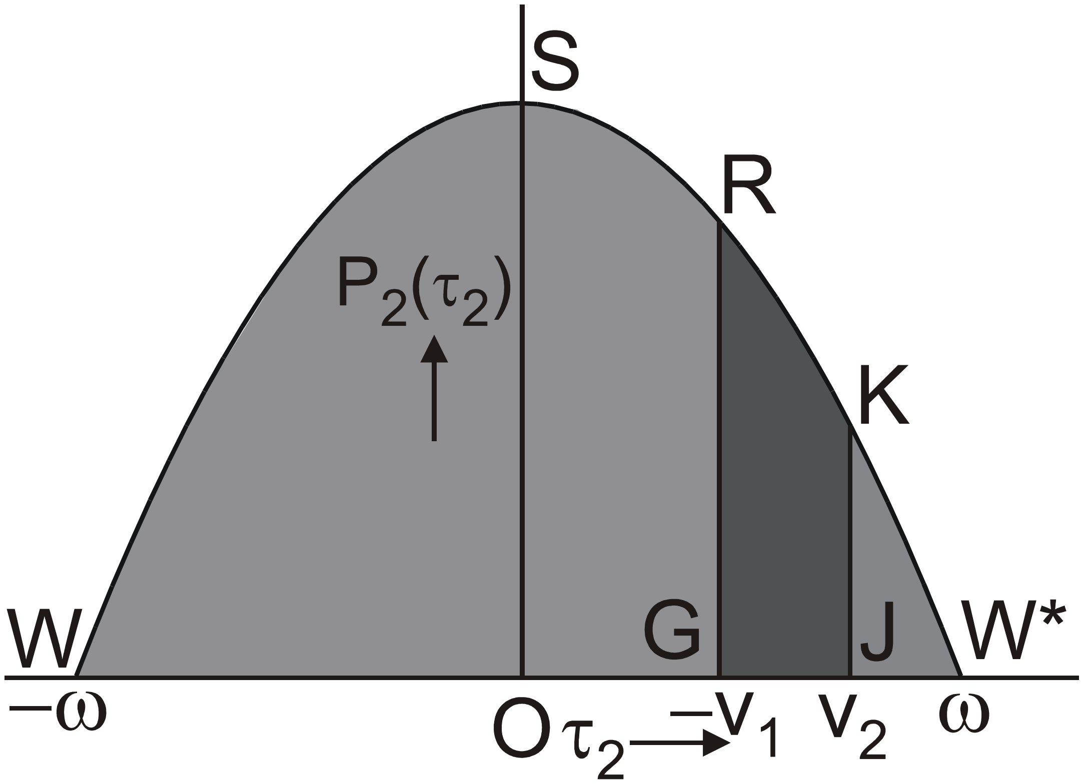



Figure 5. The effect of a marginal decrease in $v_1$ for $v_1 + v_2$ in the third interval of $\tau$

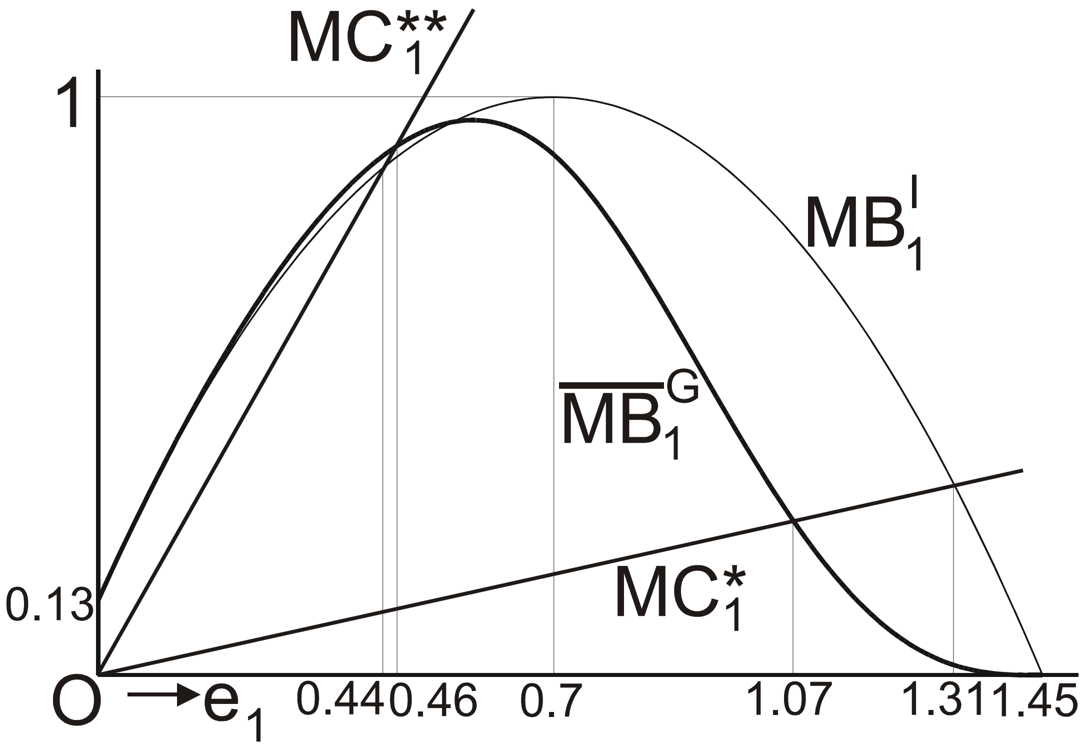



Figure 6. Marginal benefits of agent 1's effort, individual and group rewards compared