

On Coordination of Abatement in Voluntary Agreements*

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Abstract

The negotiated agreement (NA) — the strictest form of a voluntary agreement — is modeled as a coordination device to exchange emission abatement offers between firms to preempt environmental regulation. We find that the NA is Pareto efficient and that the potential cost savings to be derived from a NA increases with firm heterogeneity. The NA realizes almost all of the cost savings when the potential cost savings are low and it realizes only a fraction of the cost savings if the savings are potentially high. Consequently, the cost savings under a NA are typically smaller than those achievable by market-based policy instruments, in spite of the NA being Pareto efficient.

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1 Introduction

One of the main merits to the use of voluntary agreements (VAs) often put forward is that they offer a more practical and flexible approach in dealing with environmental pollution compared to traditional (direct) regulation. Because of this, the use of VAs has expanded enormously in the last couple of decades across the United States, Europe and Japan ([20], [23]). However, despite the presence of the inherent flexibility and given that firms voluntarily are willing to participate in such programs to cut back pollution, the natural question arises as to how firms succeed in allocating abatement tasks among each other. It is a major challenge by which the participating firms have to find a response in order to come to an agreement on how much each of them will contribute in terms of abatement. Surprisingly, the vast literature on VAs has hardly touched upon the abatement allocation problem. This paper aims to fill this gap.

Depending on the specific design of VAs, participants may differ with respect to the degree of commitment. In this paper, our focus is on the strictest type: the negotiated agreement (NA).¹ The NA is a contract between a public authority and a firm (or group of firms) that commit to reduce pollution to an agreed upon level within a certain time period. In return for the firms' abatement commitment the authority abstains from legal intervention, or imposes some kind of regulation if firms are not responsive to emissions abatement.² We develop a model that can generate an allocation of abatement which is optimal for all participating firms in the NA. The firms' commitment to abate pollution is like contributing to the production of a public good of which the producers also act as the consumers. The consumer of the public good can neither be excluded from consuming the outcome of the collective abatement effort, nor is there rivalry in 'consuming' abatement.

In order to identify the abatement allocation, the approach applied in this paper is in the domain of voluntary public goods provision (see, e.g., [6], [10]). A common point of departure is the assumption that each economic agent considers the quantities supplied by other participants as given. In the non-cooperative Nash equilibrium representing such cases, the total supply of the public good is below the efficient level (e.g., [16]). However, some

¹See Lyon and Maxwell [20] for an extensive treatment of the different types of voluntary programs.

²Perhaps one of the earliest successes of this type of agreement was between Japan's Yokohama City council and the Isogo thermal power station on plant design and pollution control issues. Another success was in 1990 in the Netherlands when the Dutch government and the chemical sector came up with an agreement to reduce toxic waste emissions. In the mid 1990s the German government had a similar successful agreement with various industrial sectors to cut back carbon dioxide emissions.

literature — in particular the literature on matching schemes (e.g., [2], [12], [9]) — discuss incentive structures that might induce individual agents to contribute more than the amount corresponding to the non-cooperative Nash equilibrium. The approach in this paper relates to that literature but differs in two main ways: (i) we assume abatement costs to be convex increasing rather than linear; (ii) we do not assume coordination of abatement through a central planner but through a ‘market mechanism’, i.e., the sum of individual abatement quantities is the ‘market equilibrium outcome’ of an exchange between firms in the NA.

The individual firm has private knowledge of his cost function and his benefit function. Costs arise from abatement and the firm weighs them against the private expected benefits from preempting regulation, which is contingent on the regulator accepting the firms’ collective abatement offer. The firm participating in the NA maximizes its private net benefit by making abatement offers that are a function of an abatement exchange rate, which shows the amount of group abatement the supplier gets in return per unit of its own abatement: the higher the exchange rate, the higher is the individual offer. Our proposed model builds on recent developments in the so-called *aggregative* game literature (e.g., [11]) and extends Nentjes [24]. We shall demonstrate that in an abatement exchange market where firms offer abatement in return for abatement by other participants, an equilibrium is feasible, establishing a Pareto-efficient allocation of abatement in the NA.

The previous literature on NAs either assumes that the abatement allocation problem among firms does not exist³ or takes for granted that the allocation of abatement has been solved ex ante. Although Manzini and Mariotti [21] touch upon the issue by allowing heterogeneous firms to negotiate on a collective abatement proposal, they do not deal with the allocation of the firms’ individual abatement tasks. Wu and Babcock [32] focus on the efficiency of individual contracts between an individual polluter and a regulator (without a common emission target) relative to the cost of direct regulation.⁴

The main literature has predominantly concentrated on the role of the abatement target, particularly in relation to degree of stringency in comparison to direct regulation. The seminal contribution in this domain is Segerson and Miceli [26] who developed a model where the regulator negotiates with an individual firm (or an industry representative) over the level of abatement. The underlying assumption is that both sides can gain if legislative intervention

³By hypothesizing that there is only one firm or by letting an industry representative negotiate with the regulator about the emission target.

⁴See Alberini and Segerson [1] for a survey.

can be avoided by voluntarily agreeing on an environmental standard. In a similar way the role of legislative threats in triggering voluntary abatement has been explored (e.g., [27], [15], [22], [8], [13], [29]), and the role of demand considerations (green consumerism) as drivers of voluntary (over)compliance ([5]). In the spirit of Segerson and Miceli [26], Glachant [14] analyzes how non-enforceability affects the pollution abatement target under VAs when the polluter has the option to reduce the stringency of the regulator’s mandated abatement by lobbying congress. Manzini and Mariotti [21] investigate the impact on the emission target of the firm with the most aggressive attitude towards pollution control. The empirical literature on voluntary programs focuses on the motives for participation and on results in terms of pollution abatement (e.g., [4], [18], [30], [31]).

The paper proceeds as follows. In section 2, the general model will be introduced. In section 3, we derive the NA equilibrium and examine its properties. It will be shown that the equilibrium is Pareto efficient. We also show that the NA under-performs relative to market-based instruments when firms are heterogeneous. In addition, the potential cost savings that can be derived from a NA increases with firm heterogeneity. However, the NA realizes almost all of the cost savings when the potential cost savings are low and it realizes only a certain share of the cost savings if the potential savings are relatively high. Section 4 concludes.

2 The model

Consider a set of firms $\mathcal{N} = \{1, \dots, n\}$ that take part in a NA. Firm $i \in \mathcal{N}$ faces an abatement cost function $C_i(q_i)$, where q_i denotes firm i ’s level of emission abatement. As usual, $C_i'(q_i) > 0$ and $C_i''(q_i) > 0$. The expected cost of direct regulation for firm i is represented as fixed total costs, C_i^R . A firm prefers to take part in a NA rather than be regulated if it expects that the associated costs will be lower compared to being regulated, i.e., if $C_i(q_i) < C_i^R$.

The cost savings from a NA compared to direct regulation arise mainly from two sources. First, regulation may require the firm to take abatement measures that are X-inefficient, whereas the NA allows flexibility to achieve the same level of abatement at lower costs. Second, cost savings will also result if the firm’s abatement commitment is lower under the NA than the mandated level of abatement under regulation. The firm’s range of economically feasible abatement levels runs from the prevailing mandatory or voluntary levels of abatement up to the level where the efficient abatement costs are equal to the costs of regulation that is expected if the NA proposed by the firms is not accepted by the regulator. The NA does

not yield cost savings if the threat of regulation is not credible, hence it will be impossible to establish an agreement.

The aggregate amount of abatement by the group of polluters is simply:

$$Q = \sum_{i=1}^n q_i = q_i + Q_{-i}, \quad (1)$$

where Q_{-i} is the sum of abatement by all firms except firm i . The firms as a group face the possibility that regulation will be imposed onto them if $Q < \tilde{Q}$, with \tilde{Q} referring to the regulator's aspiration level. This aspiration level is assumed to be exogenous. Firms are assumed to have imperfect information about the regulator's aspiration level, which — if achieved voluntarily— would annihilate the threat of imposed regulation. Normally the authority will give an indication of its target level, but group members may expect that a somewhat lower aggregate abatement offer could nevertheless be acceptable by the environmental authority. It is implicitly assumed that the probability of preempting the regulatory cost C_i^R is increasing in aggregate abatement, Q . Denote $\rho(Q) \in [0, 1]$ as the probability of preempting regulation with $\rho'(Q) > 0$ and $\rho''(Q) < 0$ for $Q \in [\underline{Q}, \bar{Q}]$, where \underline{Q} and \bar{Q} are a lower and upper bound respectively. Thus, the term ρ represents the probability of preempting the regulatory threat, which is considered to be uniform across firms that participate in the NA. The expected (private) benefits of firm i in the NA, denoted $B_i(Q)$, can now be specified in terms of the expected avoided cost of regulation:

$$B_i(Q) = \rho(Q)C_i^R. \quad (2)$$

We assume that the probability of preempting regulation is maximal ($\rho = 1$) if aggregate abatement exceeds the level of aggregate abatement expected under regulation, i.e., if $Q \geq \bar{Q}$. Beyond this point the firm's expected benefit does not increase anymore. Marginal benefits are therefore considered to be concave increasing in abatement for $Q \in [\underline{Q}, \bar{Q}]$, i.e., $B_i'(Q) > 0$ and $B_i''(Q) < 0$.

The coordination of the firms' abatement decisions is modelled as an exchange mechanism. The participating firm is a potential consumer of the public good (aggregate abatement, Q) but also contributes to its production. A firm's single abatement offer, q_i , depends on an exchange rate, which is the quantity Q_i the firm expects to receive in return from the total group of firms per unit of its own individual abatement offer q_i :

$$p_i = \frac{Q_i}{q_i} \quad (i = 1, \dots, n), \quad (3)$$

Put differently, the individual firm acts on the expectation that for every unit of abatement it offers, it will receive Q_i units of total abatement in return.⁵ Firm i views the exchange rate as exogenous. By implication, one can rewrite (3) such that:

$$Q_i = p_i q_i, \tag{4}$$

which can be interpreted as the total abatement firm i implicitly ‘demands’ given its individual abatement supply offer.

In addition to the information on the abatement exchange rate, it is assumed firm i has perfect knowledge about its (convex) cost function $C_i(q_i)$ and (concave) benefit function $B_i(Q)$. Firm i maximizes net benefits accordingly as follows:

$$\begin{aligned} \max_{q_i} \Pi_i &= B_i(Q_i) - C_i(q_i) \\ \text{s.t. } Q_i - p_i q_i &= 0. \end{aligned} \tag{5}$$

The first-order conditions to (5) are:

$$p_i B'_i(Q_i) = C'_i(q_i), \tag{6a}$$

$$Q_i - p_i q_i = 0. \tag{6b}$$

Substituting (6b) into (6a) and writing the endogenous variable q_i as a function of the exchange rate p_i transforms the first-order conditions into firm i 's abatement supply function:

$$q_i = q_i(p_i), \tag{7}$$

where $q'_i(p_i) > 0$ and $q''_i(p_i) < 0$. A firm's abatement offer progressively increases with the exchange rate so long as the marginal benefits of abatement are positive.⁶ The intuition is simple. Equation (6a) shows that for exchange rates $p_i > 1$ the firm's marginal benefit of abatement increases whilst a higher marginal cost of abatement is incurred. Marginal benefits increase when the exchange rate increases because the firm gets more total abatement per unit of its own abatement.⁷

The coordination of abatement is modeled as a market in which the firms act as producers of the public good — supplying individual abatement quantities q_i — while at the same time

⁵ Alternatively, these exchange rates give an indication of the degree of reciprocity in the abatement negotiations.

⁶ See the appendix for the formal proof.

⁷ Note that $p_i = 1$ is the non-cooperative Nash solution. In our model, with exchange rates $p_i > 1$, marginal costs (hence abatement) are higher than in the non-cooperative Nash equilibrium.

act as consumers by demanding total abatement Q_i . In equilibrium, the abatement exchange rates are such that total abatement supply of all firms meets the demand of every single firm. The firm's abatement supply (7) multiplied with the exchange rate p_i defines the firm's aggregate abatement demand as defined in (6b). Since total abatement Q is a public good and available to all firms in the NA, an equilibrium only exists if all firms demand the same quantity, implying:

$$Q_i = Q = \sum_{i=1}^n q_i \quad (i = 1, \dots, n). \quad (8)$$

With n abatement demand functions (6b), n abatement supply functions (7) and n equilibrium conditions (8), one can solve q_i, p_i, Q_i and Q . In equilibrium the vector of individual exchange rates is such that the firms' individual abatement supply offers sum up to the total supply of the public good (that is, aggregate abatement), which is equal to the quantity demanded by every single firm.⁸

3 The negotiated agreement equilibrium

We will now turn to a more detailed examination of the NA equilibrium and first discuss the properties of the equilibrium and make an assessment of its efficiency (section 3.1). This is followed by an examination of how differences in marginal costs and marginal benefits affect the allocation of abatement efforts concludes (section 3.2).

3.1 Equilibrium properties

To facilitate a transparent presentation, and without loss of generality, we will concentrate on a NA with just two firms, denoted firm 1 and firm 2. Using (6a), the first-order conditions for firm 1 and firm 2 are indicated by (9a) and (9b) respectively; using (6b) and (8) gives the corresponding market-level equilibria conditions as shown by (9c) and (9d):

$$p_1 B'_1(Q) = C'_1(q_1) \quad (9a)$$

$$p_2 B'_2(Q) = C'_2(q_2) \quad (9b)$$

$$p_1 q_1 = Q \quad (9c)$$

$$p_2 q_2 = Q. \quad (9d)$$

⁸See Kryazhinskii et al [19] for a formal proof of the equilibrium existence as well as a description of the (dynamic) adjustment process towards the equilibrium. They show that with strictly convex cost functions and strictly concave benefit functions the equilibrium is unique.

We will use rearranged forms of these first order conditions to support the actual assessment of the equilibrium properties. Using (9c) and (9d), dividing (9a) by (9b) and rearranging gives:

$$\frac{q_2}{q_1} = \frac{C'_1(q_1) B'_2(Q)}{C'_2(q_2) B'_1(Q)}. \quad (10)$$

Since $Q = \sum_{i=1}^2 q_i = q_1 + q_2$, equation (9c) can be written as $p_1 = Q/q_1 = (q_1 + q_2)/q_1 = 1 + q_2/q_1$. Using this expression, (9a) then reads $C'_1(q_1) = (1 + q_2/q_1)B'_1(Q)$. Substitution of (10) into the latter expression yields (11a). Equation (11b) can be obtained by analogy:

$$B'_1(Q) + \frac{C'_1(q_1)}{C'_2(q_2)} B'_2(Q) = C'_1(q_1), \quad (11a)$$

$$B'_2(Q) + \frac{C'_2(q_2)}{C'_1(q_1)} B'_1(Q) = C'_2(q_2). \quad (11b)$$

Firms will participate in a NA only if it raises their net benefits compared to non-participation. To prove that the equilibrium is a Pareto efficient outcome we first derive the first order conditions for Pareto efficiency, which are then being compared with (11a) and (11b). Pareto efficiency here implies maximizing the net benefits of firm 1 while not decreasing the net benefits of firm 2. Formally:

$$\begin{aligned} \max \Pi_1 &= B_1(Q) - C_1(q_1) \\ \text{s.t. } \Pi_2 &\geq B_2(Q) - C_2(q_2) \end{aligned} \quad (12)$$

Solving (12) yields the following first order conditions for achieving Pareto efficiency:⁹

$$B'_1(Q) + \frac{C'_1(q_1)}{C'_2(q_2)} B'_2(Q) = C'_1(q_1), \quad (13a)$$

$$B'_2(Q) + \frac{C'_2(q_2)}{C'_1(q_1)} B'_1(Q) = C'_2(q_2). \quad (13b)$$

Comparing (13a) and (13b) with the first order conditions of the NA equilibrium indicated by (11a) and (11b) respectively reveals that they are identical, i.e., the NA is Pareto efficient. This implies that in a NA where firms can make abatement offers there is no room for any firm to increase its individual net benefits without harming the net benefits of other firms. Therefore,

Proposition 1 *The equilibrium achieved through bidding on (reciprocal) emissions abatement is Pareto efficient.*

⁹See the appendix for the derivations of this optimization problem for the general n -firm case.

From equations (11a), (11b), (13a) and (13b) it can be seen that the NA is Pareto efficient even though the condition for full cost efficiency — where marginal costs are equalized — is *generally* not met, i.e., $C'_1(q_1) \neq C'_2(q_2)$. Furthermore, also aggregate marginal benefits could be higher or lower relative to marginal abatement costs. As a next step let us examine how this heterogeneity affects the equilibrium.

3.2 The impact of firm heterogeneity on the NA equilibrium

Table 1 summarizes the main possible configurations that can be distilled from the first order conditions of the NA equilibrium shown by equation (10).

Table 1: Possible configurations of the NA equilibrium with two firms

$C'_1 = C'_2$ and $B'_1 = B'_2$	$C'_1 < C'_2$ and $B'_1 = B'_2$	$C'_1 = C'_2$ and $B'_1 > B'_2$
$q_1 = q_2$	$q_1 > q_2$	$q_1 > q_2$
$p_1 = p_2$	$p_1 < p_2$	$p_1 < p_2$
$C'_1 = C'_2$	$C'_1 < C'_2$	$C'_1 > C'_2$
$B'_1 = B'_2$	$B'_1 = B'_2$	$B'_1 > B'_2$
$B'_1 + B'_2 = C'_1 = C'_2$	$C'_1 < B'_1 + B'_2 < C'_2$	$C'_2 < B'_1 + B'_2 < C'_1$

The first column of Table 1 with homogeneous benefit and cost functions will serve as the benchmark. In this case all terms on the LHS and RHS of (10) are equal to one, including the abatement exchange rate q_1/q_2 . Consequently all equations in the first column of Table 1 are equalities. Equal marginal costs for firm 1 and 2 means that the NA attains full cost efficiency. The last entry in the first column, stating that the marginal abatement costs are equal to the sum of marginal benefits from abatement, is identical to the well-known first order condition for the optimal provision of a public good. From (8) it follows that in case of n homogeneous firms, $p_i q_i = n q_i$ and $p_i = p = n$. The internalization of the aggregate marginal benefits in the decision of each firm makes that for the individual firm the marginal benefits are raised with a factor n compared to the non-cooperative (Nash) solution, hence the marginal cost and abatement will therefore exceed the non-cooperative Nash equilibrium values.

Now let the marginal benefit functions still be identical (implying $B'_1(Q)/B'_2(Q) = 1$) but assume firm 1 and firm 2 are the low and high marginal abatement cost firm respectively. Starting from the benchmark values $q_1 = q_2$, we then have $C'_1(q_1) < C'_2(q_2)$. Consequently $q_2/q_1 > C'_1(q_1)/C'_2(q_2)$. However, the equilibrium condition (10) requires $q_2/q_1 = C'_1(q_1)/C'_2(q_2)$. This can only be realized by raising q_1 relative to q_2 , which lowers q_2/q_1 while

pushing up $C'_1(q_1)/C'_2(q_2)$ until equality is attained. Therefore, the equilibrium has the property $q_2 < q_1$ and $C'_2(q_2) > C'_1(q_1)$. From the abatement exchange rate definitions it follows that in equilibrium $p_2 > p_1$. Thus lower (higher) marginal abatement costs for firm $i \in 1, 2$ implies higher (lower) abatement, q_i . With symmetric benefit functions the firm with the lowest marginal cost has the lowest marginal cost in the NA equilibrium despite its relatively high level of abatement. However, although the low (high) cost firm increases (decreases) abatement, its marginal abatement costs still remains below (above) the level of q_1 (q_2) where marginal costs are equal. Compared to a position of equality of abatement, which might be required under direct regulation, allowing for the possibility to put in abatement offers helps firms to reduce cost inefficiency; however, full cost efficiency is not attained.

In a similar way we can find the characteristics of the equilibrium when firms are homogeneous in terms of marginal abatement cost functions but heterogeneous in terms of marginal benefit functions. Differences in marginal benefits could, for instance, result from differences in (expected) cost of direct regulation. Consider the case where $B'_1(Q) > B'_2(Q)$, as shown in the third column of Table 1. High marginal benefits from preventing regulation induces firm 1 to raise its abatement offer relative to firm 2's abatement offer. Firm 1 will accept a lower exchange rate q_2/q_1 and higher marginal costs compared to the (homogeneous) benchmark situation. The difference in marginal costs indicates that full cost efficiency is not achieved. Neither is there maximization of aggregate net benefits since the sum of marginal benefits are not equal to marginal costs. From equations (11a) and (11b) one can conclude that the marginal cost ratio $C'_1(q_1)/C'_2(q_2) > 1$, implying that firm 1 over-abates firm 2 under-abates compared to maximizing aggregate net benefits. With exchange in abatement quantities that optimal outcome cannot be realized. It would require firm 2 to increase its abatement while the marginal benefits would less than compensate its cost, hence making firm 2 worse off.

As we can see in Table 1, the low marginal cost firm and the firm with the highest cost savings from preventing regulation take the largest share in the total abatement. This confirms the intuition one would have about the obligations firms are willing to accept in a NA. However, in our model such voluntary abatement contributions are not made out of considerations of fairness or solidarity, neither are they made under pressure from other firms. They come voluntarily, out of self-interest, with the aim to maximize the individual net benefits expected from participating in the NA by raising the probability of preempting regulation.

What can we say about the NA's relative cost efficiency? Generally market-based instruments provide firms with the incentive to control pollution up to the level where marginal abatement costs are equal, which ensures full cost efficiency. Except in the special case where firms are identical in the sense that they face homogeneous marginal benefit and cost functions, it appears that marginal abatement costs are not equalized in the NA equilibrium, however. If firms are heterogeneous one firm abates too much, the other too little, and the NA does not attain the full cost efficiency as would be the result under market-based schemes. Thus, in cost efficiency the NA remains behind what market-based instruments can achieve. The efficiency gap compared to market-based instruments is larger the more heterogeneous firms are in both their marginal abatement cost functions and in their marginal benefit functions. Consider, for instance, the second column of Table 1. Raising the marginal cost function of firm 2, $C'_2(q_2)$, has the effect that $C'_1(q_1)/C'_2(q_2) < 1$ is decreasing in equation (11a) and increasing $C'_2(q_2)/C'_1(q_1) > 1$ in (11b). In other words, the larger the difference in marginal cost functions the larger is the discrepancy between marginal costs in equilibrium and the lower is the cost efficiency. In a similar way it can be demonstrated that raising the high marginal benefit function $B'_1(Q)$ increases $C'_1(q_1)/C'_2(q_2) > 1$ and decreases $C'_2(q_2)/C'_1(q_1) < 1$ in equilibrium. The larger the difference in marginal benefits (reflecting differences in the expected costs of regulation) the larger is the discrepancy between marginal cost and the less cost efficient the NA is. In sum:

Proposition 2 *In case firms are heterogeneous the negotiated agreement is less cost efficient compared to market-based schemes and the relative efficiency gap increases with firm heterogeneity.*

Equations (11a) and (11b) show that for heterogeneous firms the sum of marginal benefits is not equalized to the efficient marginal cost level in equilibrium but lies somewhere between the low and high marginal abatement cost. The economic intuition is that in the Pareto efficient NA equilibrium the probability that the regulator will accept and endorse the NA is not optimized. There is a loss of aggregate net benefits due to setting aggregate abatement either below or above the optimal level. A value of aggregate abatement lower than optimal means a higher probability that the NA will not be endorsed by the regulator; aggregate abatement higher than optimal increases the probability that the abatement offered in the NA exceeds the level of abatement the regulator would have accepted.

These findings give food for scepticism about the NAs cost efficiency. Although the NA performs better than regulation there are strong arguments to rate it lower than market-based instruments in this sense. Furthermore, it is generally accepted that the uniformity of abatement requirements is a major cause of the cost inefficiency of direct regulation. If firms are more or less identical, and consequently the abatement costs and expected cost of regulation are rather similar, uniform performance standards will not lead to large differences in marginal costs and can subsequently be tagged as ‘reasonably’ efficient. In this case, cost savings from a NA — instead of being regulated — will be low. The result is different when firms are heterogenous in terms of abatement costs. If such a situation applies, potential cost savings will be large under uniform regulation. However, we have shown that under these circumstances the NA does not succeed in bringing marginal costs together and a fair share of potential cost savings will not be reaped. The intuitive explanation is that the low cost firm refuses to expand abatement further because the NA would become more costly than regulation and the high cost firm cannot reduce its abatement because the low cost firm simply would not accept that. The conclusion is that the NA realizes almost all potential cost savings when those savings are low and that it realizes only a certain part if potential cost savings are high.¹⁰

4 Conclusions

This paper presents a model that coordinates and allocates emissions abatement between firms that participate in a voluntary agreement. We concentrate on the strictest form of a voluntary agreement, i.e., the negotiated agreement (NA). The NA is modeled as a mechanism that steers the participating firms’ voluntary exchange of pollution abatement offers. A firm offers emissions abatement in response to proposed abatement exchange rates, which indicate how much *aggregate* abatement a firm receives in return from the total group of firms per unit of its own individual abatement offer. In equilibrium the abatement exchange rates are such that the collective abatement offer equals each individual firm’s demand for abatement. We find that the NA equilibrium is Pareto efficient and that firms with low marginal abatement costs and/or high marginal benefits take the largest share in total abatement.

Given that only quantities of abatement can be traded, and monetary side payments are

¹⁰Evidently, in case firms are heterogenous the introduction of side payments would allow firms to achieve a fully cost efficient allocation of abatement. Side payments here could reflect a scheme of permit trading as a complement to the NA, as shown in Nentjes et al. [25].

ruled out, no firm can improve its net benefits in equilibrium without hurting the net benefit of another firm. The NA equilibrium is therefore Pareto efficient. However, one can tag the NA to be *constrained* Pareto efficient. The implication is that not all potential cost savings are realized and aggregate abatement is either too low or too high compared to fully optimizing the probability that the regulator will endorse the NA and abstains from regulation.

Further, although the NA delivers cost savings compared to direct regulation, marginal abatement costs are not equalized across firms if firms are heterogeneous. Given the well-known feature of equalized marginal abatement costs under market-based environmental policy, the NA's cost efficiency is therefore lower compared to market-based instruments. The NA is *modestly* cost efficient when firms are heterogeneous in abatement costs and potential cost savings are large; the NA is *highly* cost efficient when firms are homogeneous in abatement costs and potential cost savings are small.

A Appendix

Derivation of equations (13a) and (13b)

We solve the objective function for the general case with n firms. The maximization problem here is $\max_{q_i} \Pi_i = B_i(Q) - C_i(q_i)$ subject to $B_j(Q) - C_j(q_j) \geq \Pi_j$, ($j \neq i$). The Lagrangian accordingly reads:

$$\mathcal{L}_i = B_i(Q) - C_i(q_i) + \sum_j^{n-i} \lambda_j [B_j(Q) - C_j(q_j) - \Pi_j] \quad i = 1, \dots, n; i \neq j, \quad (14)$$

where λ_j and μ are the Lagrange multipliers. The first-order conditions are:

$$\frac{\partial \mathcal{L}_i}{\partial q_i} = B'_i(q_i) - C'_i(q_i) + \sum_j^{n-i} \lambda_j B'_j(Q) = 0 \quad (15a)$$

$$\frac{\partial \mathcal{L}_i}{\partial q_j} = B'_i(q_j) + \lambda_j B'_j(q_j) - \lambda_j C'_j(q_j) = 0 \quad (\text{for all } j \neq i) \quad (15b)$$

$$\lambda_j \geq 0 \text{ and } \lambda_j = 0 \text{ if } B_j(Q) - C_j(q_j) > \Pi_j \quad (15c)$$

where (15c) is the usual complementary slackness condition. Eq (15a) can be rewritten as $B'_i(q_i) + \sum_j^{n-i} \lambda_j B'_j(Q) = C'_i(q_i)$ and Eq (15b) as $B'_i(q_j) + \lambda_j B'_j(q_j) = \lambda_j C'_j(q_j)$. Rewriting $B'_i(q_i)$ as $\frac{\partial B}{\partial q_i} = \frac{\partial B}{\partial Q} \frac{\partial Q}{\partial q_i}$ and $B'_i(q_j)$ as $\frac{\partial B}{\partial q_j} = \frac{\partial B}{\partial Q} \frac{\partial Q}{\partial q_j}$, where $\frac{\partial Q}{\partial q_i} = \frac{\partial Q}{\partial q_j} = 1$, one obtains $\frac{\partial B}{\partial q_i} = \frac{\partial B}{\partial q_j}$ ($i = 1, \dots, n; i \neq j$). Using this expression, from Eqs (15a) and (15b) it follows that the shadow price reads $\lambda_j = \frac{C'_i(q_i)}{C'_j(q_j)}$. Substitution of this into (15a) then results in:

$$B'_i(Q) + \sum_{j \neq i}^{n-i} \frac{C'_i(q_i)}{C'_j(q_j)} B'_j(Q) = C'_i(q_i). \quad (16)$$

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