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THE DESIGN OF VOLUNTARY AGREEMENTS IN OLIGOPOLISTIC MARKETS

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The Design of Voluntary Agreements in Oligopolistic Markets

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Abstract

This paper analyses the conditions under which a group of firms is incentivised to sign a voluntary agreement (VA) to control polluting emissions even in the presence of free-riding by other firms in the industry. We consider a policy framework in which firms in a given industry decide whether or not to sign a VA proposed by an environmental regulator. We identify the features that a VA should possess in order to incentivize firms to participate in the VA and to enhance its economic and environmental effectiveness. Under very general conditions on the shape of the demand schedule, we obtain the following results. First, a VA does not belong to the equilibrium of the coalition game when benefits from voluntary emission abatement are a pure public good. Second, in the presence of partial spillovers – i.e. when signatories obtain more benefits from the VA than non-signatories – a VA belongs to the equilibrium only if a minimum participation rule is guaranteed. Third, a VA with a minimum participation rule and a minimum mandatory emission abatement may improve welfare (and even industry profits) compared to a VA in which firms are free to set their own profit maximising abatement level.

Keywords: Voluntary agreement, voluntary approaches, new policy instruments, environmental regulation, coalition structures, emission standards.
JEL: K32, D21, Q28

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1 Introduction

Since the early 1990s, traditional environmental policy based on command-and-control regulation or on price incentives (i.e. environmental taxes and subsidies) has been challenged by the increasing popularity of various forms of voluntary commitments by firms to improve their environmental performance beyond what is required by the law. The terms "voluntary approaches" and "voluntary agreements" (henceforth VAs) are the most common labels attached to this kind of environmental policy instruments.[1]

Given the documented increased use of VAs in addressing domestic and international environmental problems (e.g. OECD, 2003), several authors have analysed their main pros and cons.[2] On the one hand, VAs' flexibility and potential to stimulate innovation and the diffusion of cleaner technologies has been emphasized. On the other, concerns have been expressed about VAs' real effectiveness and possible misuse as a tool for regulatory capture.

When studying the economic functioning of VAs, the first question that arises is "why do profit maximising firms decide to adhere to a VA? By and large, the answer falls into two main categories (Brau and Carraro, 2006): (i) VAs can *increase market demand*, and therefore profits, mainly by enhancing a firm's green reputation. (ii) VAs can be used to *achieve cost advantages*, which may take the form of avoiding the costs of public regulation designed to address the environmental problem, or technical and financial incentives granted by regulators, or advantages from information and innovation sharing among signatory firms. Specific explanations and institutional arrangements for all forms of VAs have been widely studied in the recent environmental economics

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[1] According to a well established classification (e.g. OECD, 1999; Carraro and Lévêque, 1999), the term *voluntary approaches*, refers to *unilateral commitments*, which consist of environmental improvement programs established by polluters themselves and communicated to their stakeholders; *public voluntary programs*, in which participating firms agree to frameworks and standards developed by public authorities; *negotiated agreements*, which are contracts between public authorities and industry. The term *voluntary agreements* should mainly be used for the latter two categories, but is often used to encompass all forms of voluntary commitments by firms (e.g. Glachant, 2007).

[2] See the surveys by Alberini and Segerson (2002), Lyon and Maxwell (2002), Khanna, 2001, and the books edited by Carraro and Lévêque (1999) and Baranzini and Thalman (2004). More recent references to empirical analyses are reported in Uchida and Ferraro (2007).

literature (e.g., for public voluntary programs, see Wu and Babcock, 1999; Lyon and Maxwell, 2003; Glachant, 2007; for negotiated agreements, Segerson and Miceli, 1998; Manzini and Mariotti, 2003; for unilateral commitments, Bagnoli and Watts, 2003; Lutz, Lyon and Maxwell, 2000).

Most of these articles restrict their analysis to the bargaining process between an industry representative (or monopolist) and a public regulatory body, or to the strategic interactions among firms which offer environmentally differentiated products. A less researched area has focused on the interactions between firms that negotiate a VA with the environmental regulator. In this setting, it is important to take into account the fact that the benefits firms gain by adhering to a VA often exhibit some degree of non rivalry and non excludability, i.e. once signed and implemented, the VA yields positive spillovers to non signatories (e.g. see Dixit-Olson (2000), Xepapadeas-Passa (2004) and Segerson-Dawson (2008) for models with homogeneous firms; Lutz *et al.*, 2000 with heterogeneous firms). Interactions among firms are very important for the design of a VA, given that a problem of free-riding is likely to arise.

This paper focuses on VAs between several firms and an environmental regulator and analyses whether firms in a given industry are actually incentivised to sign a VA when the benefits derived from the agreement may be enjoyed not only by the signatory firms, but may also spill over to others. For example, increased market demand resulting from a green marketing strategy that publicises the adoption of a new environmentally-friendly production process, may benefit all firms in the industry, rather than just those using the new process. Alternatively, if a group of firms can prevent implementation of a cost-ineffective regulation by undertaking a VA, all firms in the industry will benefit therefrom, not only those that sign the VA. A share of these benefits *can* be exclusive (depending on the type of marketing strategy or regulation); but at least some portion of these benefits will be enjoyed by firms that do not adhere to the VA. In the light of these considerations, a VA can be considered as a public good (although often an 'impure' one). A firm's decision whether or not to adopt a VA is therefore strongly affected by incentives to free-ride. This situation is widely discussed in the public finance and industrial organisation literature, where it is often argued that the incentives to free-ride are so strong that no public good is actually provided (or no R&D is carried out, or no information is collected).

In our setting, the incentive to free ride may result in no VA being implemented. However, the literature on international environmental agreements (IEAs) on global commons has shown that even in those cases where a good is purely public, a number of agents – in this literature sovereign countries – may decide to pay the cost of providing the public good (technically, they form a coalition within which the burden of providing the public good is shared).[3] If the public good is imperfect, then the coalition size usually increases (Yi, 1997, 2003; Carraro and Siniscalco, 1997). It is therefore important to assess whether these results also apply to the case of VAs, and above all under what conditions a 'coalitional VA' emerges, i.e. a group of firms decides to sign the VA even if other firms choose to free-ride.

This kind of analysis has already been performed by Dawson and Segerson (2008). They assume that the benefit provided by the VA can only be obtained if an industry-wide environmental target – set by the regulator – is met. Each firm knows that the VA will be beneficial only if a group of firms is committed to achieving the industry's abatement target defined by the regulator. If this is not the case, all firms will be penalised. The structure of the VA is such that the regulatory body cannot make any differentiation contingent on firms participation in the VA, and its signing can therefore be seen as a pure public good. At equilibrium, some firms sign the agreement in order to meet the target, even if the remaining firms free-ride, and are indifferent between being in the coalition or behaving as singletons.

The approach adopted in this paper is somewhat related to the one described above, but enables us to analyse a more general situation. We consider a policy scenario where a binding government policy (e.g, a carbon tax) is likely to be enforced unless a concerted effort by a polluting industry, in terms of costly emission reduction, is made within a VA scheme. The latter *may* foresee *signatory-firms specific* advantages (e.g. in terms of tax reduction, or financial and technical assistance) for individual and joint over-compliance, but also imply the industry-wide advantage of abolishing (or reducing the likelihood of) the binding government policy. Hence, the general case we allow for here has the following characteristics:

First, spillovers are modelled such that VAs which are both pure

[3] See the seminal papers by Carraro and Siniscalco (1993), Barrett (1994); and the surveys by Finus (2003), Barrett (2002) and Carraro (2003).

or impure public goods can be considered. We model free-riding incentives as a continuous function of the voluntary abatement effort undertaken by firms, thus allowing for more general cases of self-regulation.

Secondly, the costs and benefits that derive from adhering to the VA depend not only on the abatement agreement fulfilled by a single signatory firm, but also on the abatement levels implemented by the other signatories. These benefits accrue as more firms join the coalitional VA. This introduces an additional form of interaction amongst firms that will be shown to play an important role.

Third, there is no industry-wide environmental target fixed in advance, but the regulator can choose between two different types of VA. Namely, one in which firms are free to set their own optimal abatement level by maximising profits and minimising regulatory net costs, and one in which a minimum abatement level is imposed on each firm and a minimum threshold set on the number of firms entering into the agreement.

Within this framework, the features of a coalitional VA are investigated in a model without specific functional form assumption on market demand. We focus in particular on the conditions under which at least some firms adopt the VA. And we devote special attention to the policy design implications of the analysis. VAs are often criticised – at least in those cases in which they do not foresee an explicit environmental target – for being cost-effective but environmentally ineffective, because firms within a VA tend to pre-empt regulations or access subsidies but achieve poor emission reductions. This paper examines this criticism of VAs and discusses its proper design in terms of minimum mandatory requirement (a minimum abatement target or other policy measures), and minimum number of participants.

From a positive viewpoint, we find that VAs do not belong to the equilibrium of the coalition game in the case of a pure public good, i.e. when spillovers are such that all firms benefit equally from the abatement achieved by the signatories, unless an ad hoc assumption is made (namely, "coalition unanimity" when the profitability of the VA ceases, similarly to Dawson and Segerson's, 2008). In this sense, one can interpret our results as a generalisation of Dawson and Segerson's results. Second, in the case of an 'impure public good', namely partial spillovers, the VA is not an equilibrium of the coalition game unless the regulator imposes a minimum participation constraint for it to come into force. In this case, if the minimum participation constraint is met, then strategic interactions induce all firms to sign the VA. Therefore, under fairly general conditions, either no firms sign the VA or all firms sign it. This is another important difference compared to the literature on IEAs, where usually a subset of agents (countries) decides to sign the agreement (a partial coalition is formed).

As for policy design issues, we examine the way in which a regulator should design the VA in order to increase both the number of signatories and the VA's economic and environmental effectiveness. In addition to the opportunity to discriminate, with specific devices, between signatory and non signatory firms, we show that setting a minimum threshold on the number of participants for the VA to enter into force is an effective instrument for neutralize firms' incentives to free ride. Moreover, we find that a VA with a minimum firm-specific mandatory regulation may represent a welfare improving policy *vis à vis* one where firms are free to set their own optimal abatement level, a result usually referred only to models of product differentiation (e.g. Crampes and Hollander, 1995; for unilateral commitments, see Arora and Gangopadyay, 1995; Lutz *et al,* 2000). More surprisingly, firms' profits may also increase (within a specific parameter interval), since a regulation in an oligopolistic setting may induce firms to adopt cartel-like production levels (this result is similar to those contained in Dung, 1993; Katsoulacos and Xepapadeas, 1996 for taxation; and Farzin, 2003, Farzin-Akao, 2006 for quality standards; but has not yet been shown for VAs). Finally, "closed membership rules" should be avoided in the VA given the presence of incentives for signatory firms to limit the maximum number of participants in the agreement.

The remainder of the paper is structured as follows. Section 2 describes the main features of the VA model. Section 3 studies the equilibrium of the game and identifies the main properties of the equilibrium 'coalitional' VA. Section 4 discusses the policy implications of our analysis and further develops the model by analysing the effects of a minimum mandatory abatement target. Finally, the main results of the paper are summarised in Section 5, where some directions for further research are also outlined.

2 Regulatory-cost minimising VAs with intra-industry spillovers

As previously stated, there are several benefits that firms could reap by signing an environmental VA. In this paper, we focus on benefits arising from the expected reductions of firms' production costs. This includes both absolute cost reductions (due for example to co-operation on innovation),[4] and relative cost reductions (e.g., due to the pre-emption of a regulatory threat. Cf. Segerson-Miceli, 1998).[5]

In our analysis we consider the possibility that only a subgroup of firms belonging to the industry decides to sign the VA. In this particular situation, all or part of the benefits gained by signatory firms may spill over to the remaining firms in the industry. Let the share of total benefits that spill over to non-signatory firms be denoted by β, with $\beta \in [0,1]$. Full spillovers (i.e. the pure public good case) occur when $\beta =$ 1. Otherwise, partial spillovers occur. From a positive perspective, allowing for asymmetric benefits (i.e. partial spillovers) is important because regulatory authorities do often discriminate between firms adhering and those not adhering to voluntary initiatives. This occurs, first, when VAs allow participants to access technical or financial incentives. Second, and most importantly, when VAs are mainly aimed at pre-empting a mandatory threat. In Europe, this is particularly the case for some policy mixes, such as the Danish CO_2 agreement scheme (see Millock and Krarup, 2007) and the British 'Umbrella Agreements' (Cf. ten Brink, Morère and Wallace-Jones, 2003; de Muizon and Glachant, 2004). In both cases, public authorities clearly discriminate between participants and non participants, by granting the former high reductions on CO_2 taxations.[6]

The benefits from these expected cost reductions are assumed to possess two important features. First, benefits increase with abatement levels, i.e. the capacity of a VA to offset the implementation

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[4] This group also comprises VAs with 'information sharing activities' (Glachant, 1999; Cavaliere and Frontoso Silvestri, 2002); innovation oriented' VAs with R&D activities by firms (Aggeri and Hactuel, 1999); VAs with 'effects on input prices' (e.g. Konar and Cohen, 2001); 'tailored regulation schemes' (Boyd and Blackman, 2002) and transaction cost reductions (Segerson and Miceli, 1998).

[5] This second group also includes VAs that affect both a legislative threat and the attainment of subsidies by a regulator (Lyon and Maxwell, 2003) and VAs mainly characterised by a regulator's subsidy (e.g. Wu and Babcock, 1999), which may take the form of technical assistance, beneficial public disclosure or financial incentives.

[6] As is well known, energy-intensive firms in Denmark can considerably reduce their carbon tax payments by signing a VA with the Danish Energy Agency in which they commit to undertake investments for energy efficiency (for an evalutation of these policy interventions see Bjørner and Jensen, 2002). In the UK, signatories of the Climate Change agreements obtain an 80% reduction of the climate change levy.

of mandatory regulation (or to gain direct incentives), increases with the level of emission abatement effected by each signatory firm. Second, benefits are increased by the cooperative behaviour of firms that sign the VA and the number of participants. An example of framework compatible with these hypotheses is the case studied by Aggeri and Hatchuel (1999), where firms adopting a VA agree to common technological innovation efforts in order to attain a cleaner production goal. Another example is provided by Maxwell, Lyon and Hackett (2000), who analyse how firms can jointly undertake self-regulatory initiatives so as to influence citizens' demand for mandatory regulation, and consequently modify the regulator's decisions. To account for the above features of observed VAs, we assume that firms that sign a VA have expected costs lower than those they would face were mandatory policy measures applied. Moreover, the cost reduction increases as more firms sign the VA and as the abatement effected by these firms increases.

2.1 The model

Consider an oligopolistic industry with n identical firms that share the same technology and compete à la Cournot. In this framework, three externalities can be identified: (i) a Cournot (or 'combined-profits') externality that leads firms to excess production at the Nash equilibrium compared to the case where they behave cooperatively) and choose abatement levels without maximising overall industry profits;[7] (ii) a VA participation externality, through which the benefit achieved by a firm increases with the abatement effected by the other signatories;[8] (iii) a public good externality, which enables a non-signatory firm to receive a

[7] From a firm's perspective, this kind of externality exists in all market structures different from cartels, i.e. perfect competition, monopolistic competition and Cournot competition. This effect is referred to as 'combined-profits' externality in the R&D coalition literature (e.g. Kamien, Muller and Zang, 1992).

[8] In the case of the policy mixes cited above, as well as in other examples in climate change policies (Cf. ten Brink *et al.*, 2003), the very structured nature of the schemes apparently seems to eliminate the collective nature of these VAs, i.e. each firm is faced with a take-or-leave-it offer -- irrespective of whether or not it decides to accept the scheme -- and the nature of the equilibrium seems not to be affected by the decisions of other firms. We consider this view as too simplistic. Indeed, apart from some public voluntary programs unilaterally promoted by regulators, the final written provisions of many VAs are certainly influenced by the number of polluters involved in the negotiation and the extent of the promised environmental commitments.

share β of the benefits produced by implementation of the VAs and the related behaviour adopted by the firms which sign the VA.[9]

Firms supply a homogeneous good and pollute the environment while a regulatory agency proposes a VA to reduce polluting emissions. A firm's decision variables are the production level, the amount of emission abatement, and whether or not to sign the VA proposed by the regulator. Each firm sets its decision variables by maximising profits.

The regulator decides the type of VA to propose by taking into account the consequent participation incentives and emission levels. His objective is the maximisation of social welfare. The regulator we are considering is fairly similar to that of Segerson and Miceli (1998), Glachant (2007) or Lyon and Maxwell (2003), i.e. a public authority which has incomplete control of a mandatory threat of taxation or command and control intervention, but which, by promoting the use of a VA, is able to eliminate or reduce the severity of such mandatory threat and provide firms with technical or financial incentives. A structured description in line with our framework is offered by Lyon and Maxwell (2003), who model the behaviour of a regulator that prefers a publicly subsidised and environmentally weaker VA to the promotion of a (uncertain) legislative intervention in cases of strong political opposition.[10] Note that the preference for the VA may be even more likely where real efficiency gains such as those recalled above are assumed to take place.[11]

The above choices are cast in a three-stage game. In the first stage, the regulator chooses between two main types of VAs: (i) a VA in

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[9] The latter two externalities actually originate from the same economic effect, but they differ in size (save for the case of perfect non-excludability). We keep them separate in order to better emphasize the role of their different intensity and the form of free-riding incentive.

[10] This does not necessarily conflict with the search for social welfare. Be it a lesser environmental objective than the mandatory policy, or the granting of subsidies, the regulator could simply be evaluating the certainty of the agreed voluntary environmental objective at least as the lesser environmental objectives or the cost of public funds.

[11] We agree with Lyon and Maxwell (2003) that also allowing for the genuine cost advantages related to VAs can make it too easy to reach a conclusion about the superiority of VAs. However, the focus is different here. We are not saying that VAs are always better. Nevertheless, once the VA option is on the agenda, we believe that there is still room for policy design improvement to make even a suboptimal (but feasible) policy better.

which signatory firms are free to choose their profit maximising abatement level; and (ii) a VA in which each firm is required to attain at least a minimum abatement level in order to pre-empt direct regulation.[12] In the second stage, the coalition game takes place. Given the type of VA proposed by the regulator, firms decide non-cooperatively whether or not to sign it. Each firm chooses its profit maximising strategy by taking into account its interaction with the other firms, and the implications of the second stage choice for the production and abatement decisions that will be taken in the third stage of the game. The equilibrium in the second stage is a non-cooperative Nash equilibrium and each firm's strategy space is [to sign the VA, not sign the VA]. Decisions are simultaneous and the membership rule is open (see Carraro and Marchiori, 2003; Yi, 2003 for a detailed description of these assumptions and their implications). In the third stage – the Cournot game – the n firms choose their output and optimal abatement levels simultaneously and non cooperatively (with or without the constraint on minimum abatement levels imposed by the regulator).

The formal model. Let y_i be firm i's production level. Total output is therefore $Y = \sum_{i=1}^{n} y_i$. The following conditions are needed on the demand side in order to ensure stability (Seade, 1980):

(1a) $$P(y_i)' - C(y_i)'' < 0$$

(1b) $$P(y_i)' + y_i P(y_i)'' < 0,$$

where $C(y_i)$ are the overall production costs and $P(y_i)$ is the inverse demand function, which is only assumed to be weakly convex.

The production activity is polluting and firms may plan to carry out some abatement effort e_i. Emission abatement is costly. Let us assume that firms deciding to sign a VA have an expected convex abatement cost equal to $\phi_i(e_i)$, where $\phi_i'(0) = 0$, $\phi_i'(e_i) \geq 0$ for $e_i>0$, and $\phi_i''(e_i) > 0$. Also, assume that abatement costs are independent of the emission reduction being voluntarily undertaken or in observance of a

[12] This is just one of the possible forms of minimum coactive regulation that can be introduced in the VA. Another possibility is a minimum environmental tax as in the Danish CO_2 Agreement Scheme and in the UK "umbrella agreements (see footnote 6 above).

mandatory requirement. The traditional interpretation is that of an end-of pipe-technology which absorbs pollutants.[13] A complementary interpretation, particularly suited to climate change policy agreements, is to consider $\phi_i(e_i)$ as an emission reduction cost function representing the cost from accessing a backstop emission trading market or other 'Kyoto mechanisms'. Finally, let 'A' indicate an 'Agreeing', or VA adopting firm, whilst 'NA' denotes a 'Non-Agreeing' firm.

The crucial element of the model is the total cost function TC (including both production costs $C(y_i)$ and abatement costs $\phi_i(e_i)$), which must be a reduced form of at least three variables: a) the levels of emission abatement by participants, b) the number of participants in the VA, and c) the spillovers obtained by both 'agreeing' and 'non-agreeing' firms. In order to capture these different effects, we borrow from a kind functional form specifications which can often be found in RJV or R&D coalition literature (e.g. Katz, 1986; d'Aspremont and Jacquemin, 1988; Kamien et al, 1992; Suzumura, 1992; Beath, Poyago-Theotoky and Ulph, 1998) and we assume that the adoption of a VA affects both production and abatement costs (the latter in an indirect way, as will appear from equilibrium conditions).

Let c denote the marginal production cost in the business-as-usual situation (i.e. when no VA is introduced) and let $e_{iA} - e_0$ be the increase in the abatement level agreed by a signatory firm vis-à-vis the emission abatement level e_0 achieved when no VA is available to firms.

Let us also assume that the cost advantages (whether 'regulatory gains' or real efficiency gains) obtained by a VA signatory are proportional to the incremental abatement effort $e_{iA} - e_0$.

To allow for cases in which VAs imply significant participation costs, let us reduce the previous cost advantage by a share proportional to the individual abatement effort. Let d parameterise this possible marginal cost increase following the adoption of a VA.

To model the VA participation externality, let us relate a firm's cost advantage to the number of signatories by means of a positive parameter γ.

Finally, let $K \in [1, n]$ be the number of signatory firms.

As a consequence, the VA participation externality in a

[13] For a recent analysis of the relationship between VAs and the market for pollution abatement technologies see David and Sinclair-Desgagné (2005).

symmetric equilibrium is $\gamma(K\text{-}1)(e_{iA} - e_0)$, and when all the above elements are added up, the expected total cost function of a signatory firm is:

(2) $$TC_{iA} = (c + z_{iA})y_{iA} + \phi(e_{iA}),$$

where

(3) $$z_{iA} = d(e_{iA} - e_{i0}) - \gamma\sum_{k=1}^{K}(e_{kA} - e_{k0}), \qquad d < \gamma$$

represents the net marginal cost advantages accruing to firm i only once it has signed the VA.[14] In order to set a limit to the extent of cost advantages, we allow for an upper bound e^{UB}, which can conveniently be expressed in emission abatement units. This implies that $z_{iA} \geq -e^{UB}$. In order to ensure positive production levels, we also assume that $z_{iA} \geq -c$. Without loss of generality and to keep the algebra as simple as possible, the value of the parameter γ can be normalised to 1 by introducing a parameter $\delta = d/\gamma$.[15] Hence, the expected profit function for firms which sign the VA is:[16]

(4) $$\pi_{iA} = \left\{P(Y) - \left[c + \delta(e_{iA} - e_{i0}) - \sum_{k=1}^{K}(e_{kA} - e_{k0})\right]\right\}y_{iA} - \phi(e_{iA}), \quad \delta \in [0, 1].$$

Recalling that a share $\beta \in [0, 1]$ of the benefits produced by adopting the VA spills over onto the non-signatory firms, the latter therefore have the following cost function:

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[14] We could add some structure to z_{iA} so as to formally distinguish between regulatory gains and genuine efficiency gains. While remarking again that our framework may comprise both effects, we prefer not to do so, in order to keep the analytical structure as simple as possible.

[15] Note that we are imposing $\gamma \geq d$, and of course this must be true for a Cournot-Nash competition framework. Had we allowed for the case in which $d > \gamma$, no VA could be created unless we assume that firms collude in the choice of abatement level.

[16] We usually refer to expected costs and expected profits because the cost reduction achieved through the VA is relative to the expected costs under a different form of regulation.

(5) $$TC_{iNA} = \left[c - \beta \sum_{k=1}^{K} \left(e_{kA} - e_{k0} \right) \right] y_{iNA} + \phi\left(e_{i0}\right), \qquad \beta \in [0, 1],$$

where $\phi(e_{i0})$ is the business-as-usual abatement cost, because both signatories and non-signatories may effect some abatement effort even in the absence of a VA.

While the abatement cost function is the same regardless of whether or not the VA is adopted, non-signatories do not pay the costs of implementing the VA, which is $\delta\left(e_A - e_0\right)$. Thus, their expected profit function is:

(6) $$\pi_{iNA} = \left\{ P(Y) - \left[c - \beta \sum_{k \neq 1}^{K} \left(e_{kA} - e_{k0} \right) \right] \right\} y_{iNA} - \phi\left(e_{i0}\right).$$

Finally, let us look at the regulator's behaviour. As we have said, the regulator may set a minimum abatement level ($\overline{e}$) in order to rule out the adoption of 'cosmetic agreements'. The regulator makes this choice in the first stage of the game, by anticipating how the industry will behave in the subsequent stages. Hence, the regulator decides to bind the firm to an abatement level $e_{iA} \geq \overline{e}$ if its welfare function (defined as usual by the sum of industry profits, consumers' surplus and environmental gains), when a minimum binding abatement level is imposed, is larger than in those cases where signatory firms are free to adopt their profit-maximising abatement strategy.

3 Equilibrium coalitional VAs

The equilibrium of the game described in the previous section is computed by moving backwards from the last stage. Let us first consider the case where no VA is proposed (which implies $z_{iA} = 0$) and compute the business-as-usual abatement level e_{i0}. For the sake of simplicity, let us also assume that there are no additional demand side or supply side effects induced by e_{i0} – the emission abatement undertaken regardless of whether or not a VA is in force.[17] Given the existence of a corner solution, to compute the equilibrium production and abatement levels we use the first order Kuhn-Tucker conditions, which in this case are:

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[17] Of course, these effects may exist. Here we suppose they are equal to zero in order to focus on the effects related to the VA adoption.

(7a) $P'(Y)y_i + P(Y) - c \le 0, \quad y_i \ge 0 \quad \text{and} \quad [P'(Y)y_i + P(Y) - c]y_i = 0,$

(7b) $-\phi'(e_i) \le 0, \quad e_i \ge 0 \quad \text{and} \quad -\phi'(e_i)e_i = 0,$

from which, at equilibrium, $e_{i0} = 0$, for $i = 1,2, \dots n,$ because $\phi'(e_i) > 0$ by assumption.[18] Hence, when no VA is adopted, the equilibrium output coincides with the standard Cournot production level.

When a VA is proposed to firms and the first *K* firms sign it (*K = 1, 2, …n*), the expected profit functions can then be re-written as:

(8a) $$\pi_{iA}(K) = P(Y)y_{iA} - \left(c - (1-\delta)e_{iA} - \sum_{k \ne i}^{K} e_{kA}\right)y_{iA} - \phi(e_{iA}) \quad \text{for } i = 1,\dots,K$$

(8b) $$\pi_{iNA}(K) = P(Y)y_{iNA} - \left(c - \beta \sum_{k=1}^{K} e_{kA}\right)y_{iNA} \quad \text{for } i = K+1,\dots,n$$

If no firms sign the VA, equilibrium profits are those of the standard Cournot-Nash competition framework, i.e.

(8c) $$\pi_{iNA}(0) = [P(Y) - c]y_{iNA}$$

The differentiation of (8a) and (8b), w.r.t. y_{iA} and e_{iA} respectively and w.r.t. y_{iNA}, yields the following first order conditions[19] which, jointly with the condition $e_{iA} \le e^{UB}$, define the Nash equilibrium values ($y^*_{iA}, y^*_{iNA}, e^*_{iA}$) of the third stage of the game contingent on *K* firms having signed the VA in the second stage:

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[18] This solution, for condition (7b), is unique given our assumptions on $\phi(e_i)$, and since z_{iA} equals zero when no VA is proposed. Intuitively, in a non-cooperative framework, firms will abate emissions voluntarily only if this does not constitute a net cost for them. The solution could not have been unique had we allowed for the presence of other more complicated forms of marginal cost effects arising from voluntary abatement (e.g. end-of-pipe cost modifications).

[19] The solutions to this problem are internal. We do not therefore show the weak inequality conditions for this case.

(9a) $$P'(Y)y_A + P(Y) = c + (\delta - K)e_A$$

(9b) $$(1-\delta)y_A = \phi'(e_A)$$

(9c) $$P'(Y)y_{NA} + P(Y) = c - \beta K e_A$$

where δ <1 and $Y = Ky_A + (n-K)y_{NA}$. The index *i* has been dropped given the symmetry of the equilibrium. Note that the equilibrium production and abatement level ($y_{iA}^*, y_{iNA}^*, e_{iA}^*$) are a function of *K*, the number of firms that decide to sign the VA. To clarify the notation, here and in the sequel we shall write this relationship explicitly.

The equilibrium outputs are obtained by first solving (9b) for y_A:

(10) $$y_A = \frac{\phi'(e_A)}{1-\delta} \equiv \varphi^{-1}(e_A)$$

from which $e_A = \varphi(y_A)$. Then, considering the upper bound constraint, the equilibrium value y_A^* is:

(11) $$y_A^* = \varphi^{-1}(e_A^*) \qquad \text{where} \qquad e_A^* \equiv \psi(y_A^*) = \min\begin{cases}\varphi(y_A) \\ e^{UB}\end{cases}.$$

Given that abatement costs are assumed to be convex, the abatement level is a monotonically non decreasing function of output.[20] Substituting the expression for Y^* and e_A^* in (9a) and (9c) and using symmetry again, we obtain:

(12a) $$P'(Ky_A^* + (n-K)y_{NA}^*)y_A^* + P(Ky_A^* + (n-K)y_{NA}^*) = c + (\delta - K)\psi(y_A^*)$$

(12b) $$P'(Ky_A^* + (n-K)y_{NA}^*)y_{NA}^* + P(Ky_A^* + (n-K)y_{NA}^*) = c - \beta K\psi(y_A^*).$$

Equations (12a) and (12b) implicitly define the equilibrium output levels which determine the equilibrium abatement levels. These

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[20] This result confirms the general applicability of the abatement cost specification that we have chosen.

equilibrium values (all dependent on K) can then be substituted in the profit functions (8a) (8b) to analyse the equilibrium of the second stage of the game where firms decide whether or not to sign the VA, i.e. the stage where the equilibrium number of signatories, K^*, is determined.

Second stage of the game.

Let $\pi^*_{iA}(K) \geq 0$, $\pi^*_{iNA}(K) \geq 0$ be the values of the profit functions, for signatories and non-signatories respectively, when output and abatement levels take the equilibrium values determined by eqs. (12a), (12b) and (11). A necessary condition for the existence of an equilibrium coalition is that profits for VA signatories are greater than their profits when no VA is signed, i.e.

(13) $$\Pi_{iA}(K^*) \equiv \pi^*_{iA}(K^*) - \pi^*_{iNA}(0) \geq 0 \qquad \text{for all } i=1,2,\ldots K$$

This profitability (or rationality) condition must hold jointly with the so-called stability conditions (Cf. D'Aspremont *et al.,* 1983; Carraro and Siniscalco, 1993):

(14a) $$\pi^*_{iA}(K^*) \geq \pi^*_{iNA}(K^* - 1), \qquad \text{for all } i = 1, 2, \ldots, n.$$

(14b) $$\pi_{iA}(K^* + 1) \leq \pi_{iNA}(K^*), \qquad \text{for all } i = 1, 2, \ldots, n.$$

The profitability and stability conditions are necessary and sufficient to define the Nash equilibrium of the second stage of the game. Hence, when players are symmetric, the equilibrium K^* is the largest admissible integer smaller than the unique root of the following equation:

(15) $$L(K^*) \equiv \pi_A(K^*) - \pi_{NA}(K^* - 1) = 0,$$

where $L(K^*)$ is such that $L'(K^*) < 0$, $\Pi_A(K^*) \geq 0$ for all $K \in [1,n]$, and the index i has been dropped because of symmetry.[21]

Note that, applying (14), if $L(K) < 0$ for all $K \in [1, n]$, then there is only a trivial equilibrium coalition, because the incentive to free-ride

[21] *L(K)* is usually referred to as the "stability function" (e.g., Carraro and Marchiori, 2003; Hoel and Schneider, 1997).

– $\pi_{NA}(K-1)$ - $\pi_{A}(K)$ – is positive for all $K \in [1,n]$.

Under the above fairly general functional forms, it is not possible to derive an analytical expression for K^*. Nonetheless, in the following we argue that general conclusions can be drawn. We will show that if $L(K) > 0$ for all K larger than a given value $K^\wedge$, where $1 \leq K^\wedge < n$, then the 'grand coalition' ($K^* = n$) forms at the equilibrium, provided that a coordination mechanism (e.g. a minimum participation constraint) guarantees that at least $K^\wedge$ firms join the coalition. [22] We summarise the positive results of the model in the following:

Proposition 1

Under open membership, if benefits for signatories are partially excludable (β <1), the stability function L(K) becomes positive for some $K \geq K^\wedge$ and its slope is positive. This implies $K^* = n$, i.e. all firms in the industry decide to sign the VA. If benefits for signatories are not excludable ($\beta = 1$), no firm adopts the VA.

PROOF. The proof of the proposition can be divided in three main steps or lemmas:

Lemma 1. If $\beta < 1$, then there exists a value $K^\circ = \dfrac{\delta}{1-\beta}$ such that, for all $K \geq K^\circ$ ($K \leq n$), the output of non-signatories is smaller than signatories;

Lemma 2. There exist a value $K^\wedge \geq K^\circ$ for which the stability condition is satisfied, and above which it is always positive, so that in equilibrium $K^* = n$ firms adopt the VA.

Lemma 3. For $\beta = 1$ the stability function $L(K^*)$ is negative and negatively sloped, so that in equilibrium no stable agreement will be signed by any firm.

[22] The presence of minimum participation constraint is very common in international environmental treaties. According to Rutz (2001), only 2 out of the 122 multilateral environmental agreements provided by the Center for International Earth Science Information Network do not contain any minimum participation rule. In 81 cases, the participation rule asks for a minimum number of signatories. In 22 cases, unanimity is required for the treaty to come into force, namely all negotiating countries must sign and ratify the agreement for it to be effective. In the remaining 17 cases, the minimum participation rule is coupled with other requirements, i.e. for these agreements it is not sufficient for a certain number of countries to ratify the treaty, but these countries also have to satisfy other, additional criteria.

Proof of Lemma 1.

Subtracting equations (12b) from (12a) yields:

$$P'(Y^*)(y_A^* - y_{NA}^*) = [\delta - (1-\beta)K]\psi(y_A^*), \tag{16}$$

which implies that firms signing the VA produce a higher output if and only if they have lower marginal production costs.[23] This is the case when $\delta < (1-\beta)K$, or equivalently:

$$K > \frac{\delta}{1-\beta} = K^{\circ}. \tag{17}$$

Hence, only when the group of signatories is sufficiently large, can a signatory produce more than a non-signatory. In this case, a signatory also has a larger market share. Note that the positive relationship between profits and equilibrium output implies that (17) is a necessary condition for the (internal) stability condition (14a) to be met.[24] Also note that (17) is more easily satisfied when the spillover rate β is low, and when the VA-related cost parameter δ is also low.

Proof of Lemma 2

We show that for $K \geq K^{\circ}$ the characteristics of the profits functions are such that once the critical participation threshold $K^{\wedge}$ is reached, in equilibrium $K^* = n$ firms join the VA.

First note that a lower marginal cost is only a necessary condition for signatories to have larger profits than non-participants, because signatories also pay for the emission abatement costs $\phi(e)$. This implies that profits of signatories are larger than non-signatories only for a value of K above K°. Let us denote this value with $K^{\wedge}$, where $K^{\wedge} \geq K^{\circ}$. We now show that this value generally exists independently of whether

[23] Note that y_A^* and y_{NA}^* are actually $y_A^*(K)$ and $y_{NA}^*(K)$. While we take this into account in the following analysis, we omit reporting the K argument so as to simplify notation.

[24] This conclusion is true independently of ϕ because eq. (11) implies that equilibrium abatement is a monotonically non decreasing function of output. As a consequence, the greater the function $\phi(e)$, the lower y^* and therefore the lower e^* and the value of $\phi(e^*)$.

profits increase monotonically with K for all $K=1,2,\dots,n$ or not.

Let us study the behaviour of the profit functions at the Nash equilibrium. In general, we have:

$$\frac{d\pi_i^*}{dK} \equiv \frac{d\pi\left(y_i^*, y_{-i}^*, e_A^*, K\right)}{dK} = \left(\sum_{j\neq i} \frac{\partial \pi_i^*}{\partial y_j^*}\frac{dy_j^*}{dK}\Big|_{y_A=y_A^*, y_{NA}=y_{NA}^*, e_A=\psi\left(y_A^*\right)}\right) + \frac{\partial \pi_i^*}{\partial K}\Big|_{y_A=y_A^*, y_{NA}=y_{NA}^*, e_A=\psi\left(y_A^*\right)}$$

Hence, by totally differentiating (8a) at the Nash equilibrium and using symmetry, we get:

(18a) $$d\pi_A^* = P'\left(Y^*\right)y_A^*\left\{(K-1)dy_A^* + (n-K)dy_{NA}^* + \left[\left(y_A^* - y_{NA}^*\right) + \frac{\psi\left(y_A^*\right)}{P'\left(Y^*\right)}\right]dK\right\}.$$

where the index i has been omitted because of symmetry. Let $R_A = \frac{d}{dy_A^*}\left(\sum_{j\neq i}^{n} dy_j\right)$ denote the aggregate industry reaction function and recall that R_A is negative for the so-called generalized Hahn condition for a Cournot oligopoly (Dixit, 1986).

Using (16) to substitute for $\left(y_A^* - y_{NA}^*\right)$, the previous equation becomes:

(18b) $$d\pi_A^* = P'\left(Y^*\right)y_A^*\left\{R_A dy_A^* + \frac{\left[1+\delta-(1-\beta)K\right]\psi\left(y_A^*\right)}{P'\left(Y^*\right)}dK\right\}.$$

Similarly, by totally differentiating (8b), we obtain:

(19a)

$$d\pi_{NA}^* = P'\left(Y^*\right)y_{NA}^*\left\{\left[K + \frac{\beta K\psi'}{P'\left(Y^*\right)}\right]dy_A^* + (n-K-1)dy_{NA}^* + \left[\left(y_A^* - y_{NA}^*\right) + \frac{\beta\psi\left(y_A^*\right)}{P'\left(Y^*\right)}\right]dK\right\}$$

By using (16) and the definition of R_A, this becomes:

(19b)

$$d\pi_{NA}^* = P'\left(Y^*\right)y_{NA}^*\left\{R_A dy_A^* + \frac{\beta K\psi'}{P'\left(Y^*\right)}dy_A^* + \left(dy_A^* - dy_{NA}^*\right) + \frac{\left[\beta+\delta-(1-\beta)K\right]\psi\left(y_A^*\right)}{P'\left(Y^*\right)}dK\right\}$$

Let us examine equations (18b) and (19b). First note that the terms within square brackets at the end of (18b) and (19b), respectively $[1+\delta-(1-\beta)K]$ and $[\beta+\delta-(1-\beta)K]$, become negative for all $K>K^{I}=(1+\delta)/(1-\beta)$ and $K>(\beta+\delta)/(1-\beta) = K^{I} - 1$ respectively, with $K^{I}-1>K^{\circ}$, for $\beta < 1$.[25] Then observe that the relationship between profits and signatories in the two equations depends on $\frac{dy_A^*}{dK}$, the derivative of a signatory's equilibrium production with respect to *K*.

By assuming weakly convex demand functions, and defining with K^{A} and K^{NA} the coalition size for which the equilibrium production of signatories and non-signatories is maximised, we show in the Appendix that the following conditions hold:

(20a) $\frac{dy_{iA}^*}{dK} \geq 0$ for $K\in [K^{\circ}, K^{A}]$; $\frac{dy_{iA}^*}{dK} < 0$ for $K > K^{A}$,

with $K^{A} \geq \frac{n}{2}+\frac{1+\delta}{2(1-\beta)}=\frac{n}{2}+\frac{K^1}{2} > K^{I}$;

(20b) $K^{NA} < K^{A}$

(21a) $dy_{iA}^* - dy_{iNA}^* > 0$, for $K\in [K^{\circ}, n]$ and $\beta < 1$

(21b) $dy_{iA}^* - dy_{iNA}^* < 0$, for $K\in [1, n]$ and $\beta=1$;

The first implication of these results is that *both* π_A^* *and* π_{NA}^* *may first increase and then decrease with* K. Indeed, using (20) and (21) for studying (18b) and (19b) it can be verified that profits for signatories and non-signatories certainly increase for $K \leq K^{I}$ and $K \leq K^{I} - 1$, whereas they certainly decrease for $K > K^{A}$, if the latter is smaller than *n*.[26]

Moreover, conditions (20-21) allow us to compare (18b) and (19b) and draw the following conclusions concerning the shape of the profit functions, which in turn determine the behaviour of the stability

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[25] Hence, when considering $\pi_A^*(K)$ and $\pi_{NA}^*(K-1)$, the last term within curly brackets in (18b) and (19b) has the same root $K^{I}=(1+\delta)/(1-\beta)$

[26] More precisely, $K > K^{A}$ is a sufficient condition to ensure decreasing profits in *K*. In fact, from (18b) and (19b) it can be easily seen that profits for signatories and non signatories could start to decrease even for some smaller *Ks* in the intervals $[K^{I}, K^{A}]$ and $[K^{\circ}, K^{A}]$ respectively.

function, finally showing that in equilibrium $K^* = n$ firms adopt the VA.

For $K \geq K^\circ$ and $\beta < 1$, i.e. in the interval of K in which $K^\wedge$ can exist, profits of non signatories start decreasing before profits of signatories. This can be seen by looking at the last term in (18b) and (19b), then noticing that $0 \leq \beta K \psi^{'} / P^{'}\left(Y^*\right) < 1$ for the stability condition (1a) and the non decreasing relationship between output and abatement; finally that output of non signatories starts decreasing before signatories. The same condition is even more easily verified between $d\pi_A^*(K)$ and $d\pi_{NA}^*(K-1)$, given that the last terms in (18b) and (19b) have the same root K^I.

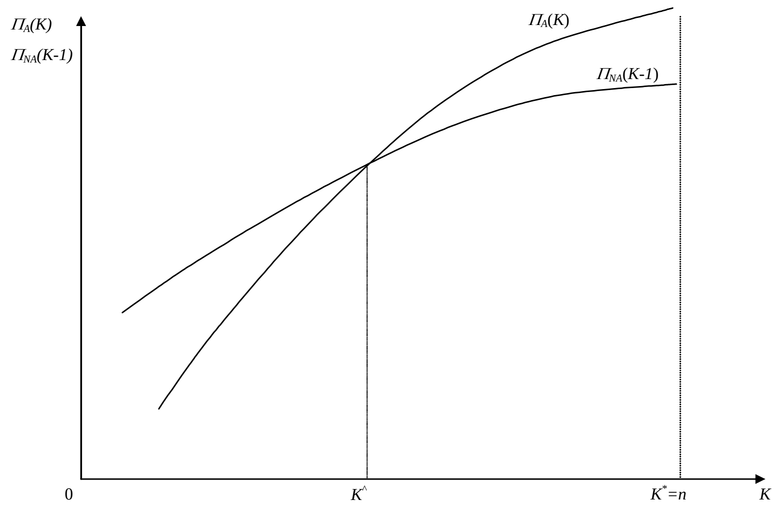
In the interval [$K^\wedge$, n], any positive difference between $\pi_A^*(K)$ and $\pi_{NA}^*(K)$ increases with K up to K=n. In fact, in the interval [K°, *n*], $\frac{d\pi_A^*}{dK} > \frac{d\pi_{NA}^*}{dK}$. Comparing (18b) and (19b) this is readily seen when $K \leq K^A$ i.e. the equilibrium production of signatories increases in *K*. For $K > K^A$, the result is recovered by the presence of the positive term $\left[\frac{\beta K \psi^{'}}{P^{'}\left(Y^*\right)} + 1\right] dy_A^* - dy_{NA}^*$ within the curly brackets in (18b).

Results i) and ii) jointly imply the existence of $K^\wedge$ as the internal stability condition $\pi_A^*(K) \geq \pi_{NA}^*(K-1)$ is satisfied and *L*(*K*) are positive for all $K \in$ [$K^\wedge$, *n*] for both a) *the case where $\pi_{NA}^*(K)$ increases with K (so that $\pi_{NA}^*(K) > \pi_{NA}^*(K-1)$) in a neighbourhood of $K^\wedge$* (see Figure 1)*;* b) *the case where $\pi_A^*(K)$ and $\pi_{NA}^*(K)$ show opposite signs or decrease in K in a neighbourhood of $K^\wedge$* (see Figure 2).

Case a). We know that $\pi_{NA}^*(K) >$ for $K < K^\circ$. However, for $K \geq K^\circ$, the positive difference between $d\pi_A(K)$ and $d\pi_{NA}(K)$ (and $d\pi_{NA}(K-1)$) allows for reversing the relationship between non signatories' and signatories' profits for some *K*. *A fortiori*, since $\pi_{NA}^*(K) > \pi_{NA}^*(K-1)$, we also have that $\pi_A^*(K) \geq \pi_{NA}^*(K-1)$, i.e. $K^\wedge$ exists.[27] Conclusion (ii) ensures that any positive difference between profits increases in [$K^\wedge$, *n*], hence *L(K)* is positive up to *K*=*n*.

[27] Of course, as in the case of K°, whose value is $\delta/(1-\beta)$, there is no guarantee that $K^\wedge \leq n$.

Figure 1: Shape of functions $\pi_A(K)$ and $\pi_{NA}(K-1)$ for $\beta < 1$ when $\pi^*_{NA}(K)$ increases in K^

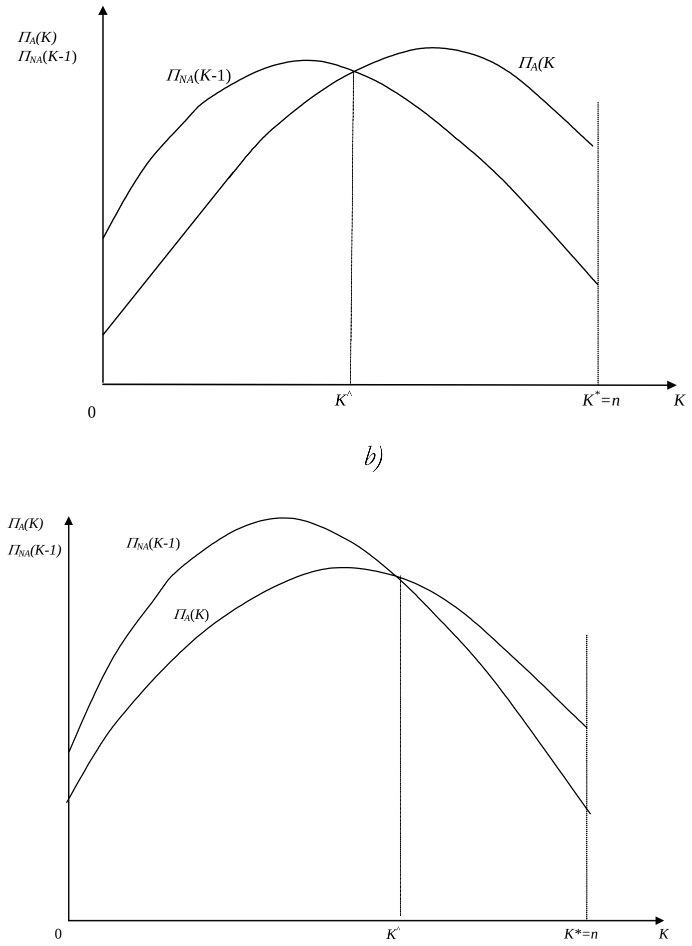


Case b). The fact that $\pi^*_{NA}(K)$ and $\pi^*_{NA}(K-1)$ start decreasing before $\pi^*_{A}(K)$ ensures that $\pi^*_{NA}(K-1)$ intercepts the profit function of signatories from above at *K*^, be it in the graphical example of Figure 2.a below or when both functions decrease in *K* (Figure 2.b). Then conclusion (ii) again ensures that *L*(*K*) is positive up to *K*=*n*.

Hence, if *K*^<*n*, *L(K)* > 0 for *K*^<*K*≤ *n*, then there is an incentive to join the coalition for all *K* ∈ [*K*^, *n*]. The equilibrium coalition is thus the grand coalition (*K** = *n*), whenever a co-ordination mechanism is introduced which induces at least *K*^ firms to sign the VA. The coordination mechanism could be a minimum participation constraint imposed by the regulator. (Cf. Carraro and Marchiori, 2003; Finus, 2003).

Figure 2: Shape of functions $\pi^*_A(K)$ and $\pi^*_{NA}(K\text{-}1)$ for $\beta < 1$ when $\pi^*_{NA}(K-1)$ decreases in K^

a)



Proof of Lemma 3:

To show that the stability function *L(K)* is negative and negatively sloped when β = 1, first note that, from (16) and (17), when β = 1 it is clear that $y^*_A \le y^*_{NA}$, since $K° = \infty$. The fact that non-signatory firms always produce at least as much as signatory firms implies that $\pi^*_A(K)$ - $\pi^*_{NA}(K) < 0$ for all $K \in [1, n]$.

Then, from (21b), we have that $dy_{iA}^{*} - dy_{iNA}^{*} < 0$ for $K \in [1, n]$, which implies that the inequality $\frac{d\pi_{A}^{*}}{dK} < \frac{d\pi_{NA}^{*}}{dK}$ always holds. Hence the negative difference $\pi_A(K)$ - $\pi_{NA}(K)$ always increases with *K*, which implies that the function $\pi_{NA}(K-1)$ is greater than $\pi_A(K)$ for all values of *K*, i.e. $L(K) < 0$ for all $K \in [1, n]$, and that this difference increases in *K*, that is $L'(K) < 0$ for all $K \in [1, n]$.

The negativity of the stability function in the whole support of *K* implies that no firm is willing to sign the VA, as previously stated in Proposition 1. As the cost effects of the VA are a pure public good, the incentive to free-ride is always greater than the benefits deriving from adhering thereto.

How can we compare our results with those obtained by Dawson and Segerson (2008), who actually state that a stable group of firms will adopt a VA in equilibrium even when non signatories equally benefit from it? We argue that the difference between the two results is only apparent, and crucially determined by the absence or presence of an additional assumption on the coalition membership rule. In their paper, Dawson and Segerson actually argue that "a level of participation that is not profitable will lead to a dissolution of the coalition." This would imply that each firm realizes that, for a K^P such that the profitability condition (13) is barely satisfied,[28] individual defection the would break the VA completely. Profits for non signatories would therefore be $\pi_{NA}^{*}(K^P - 1) = \pi_{NA}^{*}(0)$, and realizing this risk, firms belonging to a VA of size K^P would never defect.

Such "farsighted" reasoning is often advocated, but it is not actually consistent with the assumption of the usual Nash conjectures in simultaneous oligopoly games. When the whole coalition collapses when one member defects, "coalition unanimity" (often known as "game Γ") is assumed. Usually, the game-theoretic literature applies this rule to the whole support of *K*, and it is shown that with positive spillovers any $K \geq K^P$ would be an equilibrium of the game (e.g. Bloch, 2003 for a survey). Only by assuming that the threat of the whole coalition

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[28] In the coalition theory jargon, K^P can be referred to as the *minimum profitable coalition size*, which is the smallest coalition size for which a member obtains a higher payoff than if all firms are independent (e.g. Bloch, 2003).

collapsing is real just for $K = K^P$, can one obtain the minimum participation threshold K^P which satisfies the profitability condition as the equilibrium of the game.[29]

In fact, if we represent Dawson and Segerson's (2008) analysis in our framework, setting $\beta = 1$ and assuming "local" coalition unanimity in the neighbourhood of K^P,[30] we get the same result.

Proposition 2.
When firms' strategies are such that "coalition unanimity rule" for VA membership is adopted at the minimum profitable participation level K^P, a VA with K^P participant firms is an equilibrium of the game for $\beta = 1$. For $\beta < 1$, $K^* = K^P$ is an equilibrium if K^P is lower than $K^{\wedge}$, the minimum participation threshold for which signatories' profits are larger than non-signatories'; $K^* = n$ otherwise.

PROOF.
For $\beta = 1$. The internal stability condition is satisfied since the VA becomes null and void if any firm pulls out of the agreement, i.e. $\pi_A^*(K^P) \geq \pi_{NA}^*(K^P - 1) = \pi_{NA}^*(0)$. The external stability condition $\pi_{iA}(K^P + 1) \leq \pi_{iNA}(K^P)$ is satisfied since from the proof of Lemma 3 we have $\pi_A^*(K)$ - $\pi_{NA}^*(K) < 0$ and $\frac{d\pi_A^*}{dK} < \frac{d\pi_{NA}^*}{dK}$ for all $K \in [1, n]$.

For $\beta < 1$. If $K^P < K^{\wedge}$, this part of the proposition is satisfied using the above reasoning. If $K^P \geq K^{\wedge}$, non signatories are incentivised to join the VA, i.e. $\pi_{iA}(K^P + 1) \geq \pi_{iNA}(K^P)$ for all $K \in [K^{\wedge}, n]$. As a consequence, the grand coalition $K^* = n$ is achieved in equilibrium.

This ultimately confirms the generality and consistency of our model with the earlier literature.

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[29] Dissatisfaction with simultaneous coalition games has led to propose structures of "sequential games" of coalition formation. Considering the case of positive spillovers, the unique equilibrium in these games is actually K^P, (Bloch, 2003).

[30] An additional assumption they make is the orthogonality of the reactions function of non-signers, which in our model is equivalent to setting $\frac{d\pi_{NA}^*}{dK} = 0$ for $K \in [1, n]$, $K \neq K^P$.

4 The design of VAs

The characterisation of participation incentives described in the previous section has direct and important policy implications on the design of VAs in order to achieve full participation. Three recommendations follow from our results. First, the regulator should introduce a minimum participation constraint. Namely the agreement only enters into force if at least a minimum number of firms belonging to the industry decides to adhere.

Second, the regulator should design the VA in such a way that most of the benefits are reaped by signatories, thus minimising spillovers to non-signatories. This can be done, for example, through a policy-mix which penalises (or excludes from some benefits) firms which do not join the VA. Note that by minimising β, the regulator not only encourages firms to sign the VA, but also reduces the minimum participation constraint required to ensure that all firms adhere.

A third important policy implication is drawn from the likely hump-shape of the profit functions, as shown in Figure 1. This shape is the result of the asymmetry produced by introducing the VA. Firms which sign the VA have a competitive advantage over other firms, because they enjoy lower marginal production costs (if $\beta < 1$ and when a stable coalition forms). This advantage implies a higher market share, and therefore higher profits, only if some firms are excluded from the VA. When all firms sign, they all enjoy the same expected reduction in costs and therefore have the same market share. Therefore, each firm desires to obtain the benefits provided by the VA, but not to share these benefits with all firms in the industry. Thus, firms are incentivised to form a coalition that is smaller than the one in which all firms participate.[31] This is not possible under an open membership rule whereby firms are free to join or leave the VA, but it may be possible if an exclusive membership rule applies, where access is conditional on the consensus of the other signatories (Cf. Yi, 1997; Carraro and Marchiori, 2003). Consequently, if the regulator's objective is to achieve the greatest environmental benefit, he/she should design the VA in such a way that firms are unable to adopt rules or behaviours that enable them to

[31] Examples exist in which the EC Directorate-General Competition has made inapplicable the provision of a VA which restricted some advantages only to original members. E.g., see Gremminger, Laurila and Miersch (2001) on the *Eco-Emballages* waste recovering system.

exclude other firms therefrom.[32]

All the above mentioned policy design directions can be summarised in the following proposition, which directly follows from the analysis carried out in the previous section

Proposition 3.
If the regulator wants to ensure that all firms adopt the VA, then: a) benefits for signatory firms must be partially excludable, b) an adequately defined minimum participation constraint $K \geq K^{\wedge}$ must be imposed, c) an open membership rule must be enforced for the VA.

4. 1. Welfare enhancing mandatory abatement constraints

So far, we have only stressed that if VAs are properly designed, they will be signed by all firms in the industry even if some free-riding may occur. However, their effectiveness in terms of environmental control remains uncertain, given that the profit maximising abatement level set by signatory firms may be too low compared to the level of the environmental externality. This raises the question of whether a policy mix that incorporates a minimum abatement constraint associated with the possibility of firms having access to a VA scheme, can not only enhance the VA environmental effectiveness, but also improve welfare:

From a pessimistic viewpoint, one may argue that since a minimum abatement constraint increases the abatement effort required by firms, it will also reduce their output and profits and could raise equilibrium prices, thus resulting in an overall reduction in welfare (recall that welfare is defined as the sum of industry profits, consumer surplus and environmental benefits). Hence, a minimum abatement level may not be welfare improving.

From an optimistic viewpoint, i) either environmental benefits may outweigh profits and consumer surplus losses from price increase (in the literature on voluntary overcompliance, this is the case for models with vertically differentiated firms; e.g. Arora and Gangopadyay, 1995; and Lutz *et al,* 2000); ii) or the introduction of an additional bias may force firms to "pursue their own interests" by diverting them from adopting a Cournot-Nash behaviour in the choice of voluntary

[32] The case is more ambiguous if the regulator aims to maximise total welfare, since the greater environmental benefit achieved when all firms participate in the VA and the higher consumer surplus resulting from price reductions, must be measured against the lower total profit in the industry.

abatement levels.

The existence and the size of the latter ‘second best argument’ can be analysed by solving the regulator’s decision problem in the first stage of our policy framework. As previously explained, the regulator chooses between a VA in which firms are free to set their profit maximising abatement level and a VA in which a minimum abatement level is imposed. The regulator decides to impose a minimum abatement requirement only if: (i) the profit maximising abatement level is below the minimum abatement standard; and (ii) total welfare increases in the presence of a minimum abatement level.

In order to see whether the second condition can be met, let us analyse a firm’s choice in the third stage of the game when the VA requires the achievement of a minimum abatement level $\bar{e}_A$. If $\bar{e}_A < e_A^*$, then the equilibrium is the one previously derived. *Vice versa*, if $\bar{e}_A \geq e_A^*$, then a firm only chooses output in the third stage of the game, and the equilibrium is defined by the standard Cournot output choices. Indeed, if emissions by the VA adopting firms are equal to $\bar{e}_A$, the profit functions become:

(22a) $$\bar{\pi}_A = P(\bar{Y})y_A - (c + \delta\bar{e}_A - K\bar{e}_A)y_A - \phi(\bar{e}_A)$$

(22b) $$\bar{\pi}_{NA} = P(\bar{Y})y_{NA} - (c - \beta K\bar{e}_A)y_{NA}.$$

The equilibrium first order conditions are therefore:

(23a) $$P'(\bar{Y}^*)\bar{y}_A^* + P(\bar{Y}^*) = c + (\delta - K)\bar{e}_A$$

(23b) $$P'(\bar{Y}^*)\bar{y}^*_{NA} + P(\bar{Y}^*) = c - \beta K\bar{e}_A,$$

where the upper bar denotes the equilibrium values when a minimum abatement constraint exists.

Similarly to the unconstrained case, the previous equilibrium conditions are a pre-requisite for solving the second stage of the game, in which firms decide whether or not to sign the VA proposed by the regulator. In order to determine K^* - the Nash equilibrium number of firms which join the VA - we must compare profits of signatory and non-signatory firms. The results for the equilibrium coalition are essentially identical to those summarised by Proposition 1, given that the equilibrium conditions (23a) and (23b) are analogous to conditions (9a) and (9c) when no abatement constraints exist. Hence, the presence of a minimum abatement level does not modify the shape of the profit functions of signatories and free-riders. Therefore, in equilibrium, $K^{*}= n$.

This finally allows us to move on to the first stage of the game, by comparing outputs and profits in the presence and absence of an abatement constraint and by checking whether an interval exists in which welfare is an increasing function of the level of mandatory abatement. With the minimum abatement constraint output is clearly higher since it is a decreasing function of marginal costs, which are lower under a binding minimum constraint.

As for profits, note that they are identical in the two cases when $\bar{e}_A = e_A^*$. Moreover, profits for signatory firms in the unconstrained regime are maximised when $e_A = e_A^*$; thus to compare profits, we just need to evaluate the derivative $\frac{d\bar{\pi}_A}{d\bar{e}_A}$ at $\bar{e}_A = e_A^*$. By differentiating (22a) at the Nash equilibrium with respect to $\bar{e}_A$ and using the envelope theorem (so that $\frac{\partial \bar{\pi}_{iA}}{\partial \bar{y}_{iA}^*}\frac{d\bar{y}_{iA}^*}{d\bar{e}_A}=0$) we have:

$$d\bar{\pi}_{iA} = P'\bar{y}_A^*\left[(K-1)d\bar{y}_A^* + (n-K)d\bar{y}_{NA}^*\right] + \left[(K-\delta)\bar{y}_A^* - \phi'(\bar{e}_A)\right]d\bar{e}_A .$$

Again using the generalised reaction function ($\bar{R}_{iA}$), this yields

$$\frac{d\bar{\pi}_{iA}}{d\bar{e}_A} = P'\bar{y}_A^*\bar{R}_{iA}\frac{dy_A^*}{d\bar{e}_A} + (K-\delta)\bar{y}_A^* - \phi'(\bar{e}_A). \tag{24}$$

At the equilibrium of the second stage of the game, i.e. $K^{*} = n$, we have:

$$d\bar{\pi}_{iA} = P'\bar{y}_A^*(n-1)d\bar{y}_A^* + \left[(n-\delta)\bar{y}_A^* - \phi'(\bar{e}_A)\right]d\bar{e}_A ,$$

from which:

$$\frac{d\bar{\pi}_{iA}}{d\bar{e}_A} = P'\bar{y}_A^*\bar{R}_A^n\frac{dy_A^*}{d\bar{e}_A} + (n-\delta)\bar{y}_A^* - \phi'(\bar{e}_A), \tag{25}$$

where $\overline{R}_A^n$ is the 'standard' negative generalised reaction function of a symmetric Cournot oligopoly, and $dy_A^*/d\overline{e}_A$ is clearly positive as can be seen from (23a).

Hence, if the minimum standard is imposed when the grand coalition is the equilibrium coalition, profits of signatories may increase provided that:

$$\phi'(\overline{e}_A) < (n-\delta)\overline{y}_A^* + P'\overline{y}_A^*\overline{R}_A^n \frac{dy_A^*}{d\overline{e}_A}. \tag{26}$$

It can easily be verified that introducing a minimum abatement requirement when $K < n$ does not change the quality of the result.[33] Hence, equation (26) identifies an interval in which profits may be an increasing function of the minimum mandatory abatement level. The size of this interval depends on the coalition size, equilibrium output (which is affected by the set of demand and supply parameters considered) and the magnitude of marginal abatement costs, which in turn are determined by the extent of minimum abatement constraint due to convexity.

The implications of equations (25) and (26) are summarised in the following proposition.

Proposition 4:

If a coalitional VA forms, social welfare can be increased by introducing a minimum binding abatement constraint. In particular, for sufficiently low marginal abatement costs, there is an interval of abatement levels for which all components of the welfare function, including profits, increase when a minimum abatement constraint characterises the VA.

PROOF.

If there is an appropriate minimum binding abatement constraint, i.e. (26) is met, then:

(i) environmental benefits are greater, because total abatement is greater than it would be were firms free to set their own abatement levels.

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[33] Simply look at equation (24) to see that a positive interval also exists when $K < n$.

(ii) consumer surplus is higher, given that the greater reduction in costs when an emission abatement constraint is in force entails a higher level of production.

(iii) firms' profits are higher, since the regulator will choose a minimum abatement level which satisfies condition (26).

The reason behind the fact that a mandatory abatement is required in order to increase production (and possibly profits) is to be found in the positive participation externality that the VA brings to the industry. This is related to the number of participating firms and to the total extent of their effort. When this external effect is present[34] and when a firm decides its abatement effort, it also takes into account the effect that its choice will have on the marginal costs of its competitors. In particular, it realises that its decision to abate emissions will also benefit its competitors. This obviously diminishes the firm's propensity to abate emissions.

The Cournot-Nash competition scheme will consequently lead to an under-provision of abatement efforts -- as is usually the case when a positive externality is present -- because firms take the abatement choice of other members of the VA as given, instead of coordinating their abatement strategies. A minimum abatement constraint is simply a way of persuading firms to produce this external effect, moving them closer to co-operative abatement levels. In this case, although abatement costs increase, there may be an interval of emission abatement levels in which the cost increase is dominated by the higher revenue generated by higher production, which yields higher profits. Not surprisingly, the models which have unveiled this sort of effects for emission taxation (e.g. Dung, 1993; Carraro and Soubeyrain, 1996) and quality standards (e.g. Farzin, 2003) are developed in an oligopolistic framework and in the presence of free-riding incentives.

5. Conclusions

The main objective of this paper was to identify the conditions under which a group of firms in a given industry consider signing a VA the best option even when there are incentives to free-ride. These incentives arise from the non-excludability of the benefits achieved by firms adhering to the VA. Non-signatories may indeed gain all or part of

[34] Note that this effect is analogous to the 'competitive-advantage externality' in the RJV literature (Kamien et al., 1992).

these benefits as well. What conditions encourage a firm's to participate in a VA is a crucial consideration to make for the proper design of VAs in an oligopolistic framework.

We have seen that the equilibrium of the game, which describes the interaction between regulators and firms and among all firms in the industry, is characterised by several strategic incentives and external effects. The first externality is that produced by the (partial or total) public good nature of the VA. This is the origin of the afore mentioned free-riding incentives. A second strategic incentive arises from the fact that the cost saving effectiveness of the VA may increase with the number of firms adhering thereto and the extent of their abatement. Finally, a third strategic incentive is created by the oligopolistic nature of the market, which leads firms to overproduce compared to the case where they would jointly maximise industry profits and also not perfectly co-ordinate their voluntary initiatives on emission abatement.

The first effects may suggest that a VA is unlikely to be signed or, if it is signed, only a small number of firms will agree to adhere (Cf. Carraro and Siniscalco, 1993; Barrett, 1994). However, the second effect may offset the first effect, because firms know that the greater the number of signatories, the greater the benefits to be gained. We have shown that, under certain conditions concerning the extent of the spillover effect, the second effect can prevail, in particular when a minimum participation constraint is met. The third effect explains why a cut in production and/or increase of abatement levels produced by the VA may increase welfare and even industry profits.

From a positive viewpoint, by analysing the coalitional game in which firms decide whether or not to participate in the VA and taking into account the interplay of the abovementioned three strategic incentives, we have shown that:

- If the benefits that firms achieve from adhering to the VA are non excludable, i.e. non-signatories get the same benefits as signatory firms, then no firms decide to sign the VA at the equilibrium.
- If the benefits are partially excludable, i.e. signatories get more benefits that non signatories, then a VA is signed only if an appropriate minimum participation constraint is satisfied. Hence, this could be opportunely imposed by the regulator.
- However, if benefits are partially excludable, firms signing the VA may find it optimal to exclude other firms from

participating in the VA, because of the strategic advantage that a VA provides to signatories in an oligopolistic market (as seen in Section 3, a VA produces both absolute and relative cost advantages).

- Finally, the optimal voluntary abatement effort produced by the firms in the VA may be smaller than the socially optimal one, i.e. signatory firms still tend to over-emit if they are not constrained by a minimum abatement requirement.

In the light of the above results, we can make some normative policy recommendations or provide some suggestions on how to optimally design a VA in an oligopolistic industry. First, the regulator should design the VA such that mainly the signatory firms reap the related benefits (in terms of regulatory pre-emption, technological co-operation, financial and technical incentives, etc.). Free-riders should be at least partly excluded from these benefits (e.g. they are taxed whereas signatories are not; they do not receive the financial incentives, the additional flexibility or the public recognition granted to participants).

Second, the VA should contain a minimum participation clause, namely it comes into force only if a minimum number of firms accepts to adhere thereto. This minimum participation constraint reduces free-riding incentives (Cf. Carraro, Marchiori and Oreffice, 2009) and enables firms to achieve a level of benefits that creates a band-wagon effect, i.e. when the minimum number of signatories is achieved, all remaining firms find it optimal to sign the VA as well. Note that the greater the share of benefits reaped by the signatories, the lower the minimum participation constraint will be.

Third, the VA may oblige signatory firms to achieve at least a minimum individual mandatory abatement level. This can prove useful both for avoiding negligible emission reductions, and for partly offsetting the negative effects on production and profits of non-cooperative (oligopoly-specific) behaviour regarding abatement levels.

Finally, the regulator may decide to guarantee open access to the VA in order to exclude an anti-competitive, discriminatory use of the VA by some firms in the industry.

In light of the previous considerations, one can see that an optimal VA design is actually a policy mix design, that is an environmental policy where the co-existence of voluntary and 'traditional' (whether 'command and control' or 'economic') elements should be foreseen. From this viewpoint, some of the negative reputation accumulated by voluntary agreements can probably be attributed to past implementations characterized by a naïve trust in a merely self-enforcing kind of mechanism, rather than to the intrinsic unsuitability of this policy tool for implementing environmental regulation policies.

Further research could explore the issue of the optimal design of VAs in different contexts still characterized by intra-industry spillovers. For example, it would be interesting to analyse the case of 'green reputation enhancing' VAs, i.e. where the VA is adopted by firms because of its positive effects on market demand. Or to analyse cases in which signatories cooperate on abatement and/or collude on production levels. Finally, our analysis is based on the assumption of symmetric firms. The adoption of VAs in an industry with asymmetric firms (e.g. with different efficiency levels) could also be a topic of interest.

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Appendix

i. Proof of inequalities (20a)

Let us first introduce the following notation to identify the well-known negative expressions which define the second order conditions of the profit maximisation problem in a Cournot oligopoly:

$$a_{iA} \equiv P' + P'' y^*_{iA} + (K-\delta)\psi' ,$$
$$b_{iA} \equiv P' + P'' y^*_{iA} ,$$
$$a_{iNA} \equiv P' + P'' y^*_{iNA} ,$$
$$b_{iNA} \equiv P' + P'' y^*_{iNA} + \beta K \psi'$$

By focussing on weakly convex demand functions, we also have $P''(Y) \geq 0$.

Total differentiation of (12a) and (12b) yields:

$$\left(a_{iA} + P'\right) dy^*_{iA} + (K-1) a_{iA} dy^*_{-iA} + (n-K) b_{iA} dy^*_{NA} = -\mu^{iA}_K dK ,$$
$$\left(a_{iNA} + P'\right) dy^*_{NA} + (n-K-1) a_{iNA} dy^*_{-NA} + K b_{iNA} dy^*_{A} = -\mu^{iNA}_K dK ;$$

where symmetry has been exploited to add terms which are equal at the equilibrium. These equations can be re-written as:

(A.1) $$\left(K a_{iA} + P'\right) dy^*_{A} + (n-K) b_{iA} dy^*_{NA} = -\mu^{iA}_K dK$$

(A.2) $$\left((n-K) a_{iNA} + P'\right) dy^*_{NA} + K b_{iNA} dy^*_{A} = -\mu^{iNA}_K dK ,$$

where μ^{iA}_K and μ^{iNA}_K are the direct effects of a variation of *K* on the first order conditions (12a) and (12b):

$$\mu^{iA}_K \equiv \frac{\partial^2 \pi_{iA}}{\partial y_{iA} \partial K} = \left(P' + P'' y^*_{iA}\right)\left(y^*_A - y^*_{NA}\right) + \psi$$
$$= b_{iA}\left(y^*_A - y^*_{NA}\right) + \psi ,$$

$$\mu_K^{iNA} \equiv \frac{\partial^2 \pi_{iNA}}{\partial y_{iNA} \partial K} = \left(P^{'} + P^{''} y_{iNA}^*\right)\left(y_A^* - y_{NA}^*\right) + \beta\psi$$
$$= a_{iNA}\left(y_A^* - y_{NA}^*\right) + \beta\psi$$

By applying Cramer's rule to (A.1) and (A.2) we have:

(A.3) $$\frac{dy_A^*}{dK} = \frac{\begin{vmatrix} -\mu_K^{iA} & (n-K)b_{iA} \\ -\mu_K^{iNA} & (n-K)a_{iNA} + P^{'} \end{vmatrix}}{\begin{vmatrix} Ka_{iA} + P^{'} & (n-K)b_{iA} \\ Kb_{iNA} & (n-K)a_{iNA} + P^{'} \end{vmatrix}},$$

(A.4) $$\frac{dy_{NA}^*}{dK} = \frac{\begin{vmatrix} Ka_{iA} + P^{'} & -\mu_K^{iA} \\ Kb_{iNA} & -\mu_K^{iNA} \end{vmatrix}}{\begin{vmatrix} Ka_{iA} + P^{'} & (n-K)b_{iA} \\ Kb_{iNA} & (n-K)a_{iNA} + P^{'} \end{vmatrix}}.$$

Since the determinant of the denominator (denoted by *DET*) is positive (this is implied by the second order conditions for profit maximisation), the sign of (A.3) and (A.4) is determined by their numerators. In particular, we have:

(A.5a) $$\frac{dy_{iA}^*}{dK} = -\frac{1}{DET}\left[(n-K)\left(\mu_K^{iA} a_{iNA} - \mu_K^{iNA} b_{iA}\right) + \mu_K^{iA} P^{'}\right].$$

Using (16) to substitute for $y^*_A - y^*_{NA}$, we get:

(A.5b) $$\frac{dy_{iA}^*}{dK} = -\frac{\psi}{DET}\left[P^{'} + (n-K)\left(a_{iNA} - \beta b_{iA}\right) + b_{iA}\left[\delta - (1-\beta)K\right]\right],$$

which is clearly positive in a generic interval $[K^\circ, K^A]$. For a weakly convex demand function, the lowest K^A value is obtained for a linear demand function. In this case, we get:

(A.5c) $$\frac{dy_A^*}{dK} = -\frac{\psi P'}{DET}\left[n(1-\beta)+1+\delta-2(1-\beta)K\right],$$

which is positive for $K < \frac{n}{2} + \frac{1+\delta}{2(1-\beta)} = \frac{n}{2} + \frac{K^1}{2}$.

Hence $\frac{dy_{iA}^*}{dK} \geq 0$ for $K \in [K^\circ, K^A]$, where $K^A > K^\circ$ in general and $K^A \geq \frac{n}{2} + \frac{1+\delta}{2(1-\beta)} = \frac{n}{2} + \frac{K^1}{2} > K^1$ for weakly convex demand functions.

Q.E.D.

ii. Proof of inequalities (20b and 21)

From (A.4), $\frac{dy_{iNA}^*}{dK}$ is defined by the following equation:

(A.6a) $$\frac{dy_{iNA}^*}{dK} = -\frac{1}{DET}\left[K\left(\mu_K^{iNA} a_{iA} - \mu_K^{iA} b_{iNA}\right) + \mu_K^{iNA} P'\right];$$

that is, recalling that $b_{iNA} = a_{iNA} + \beta K \psi'$,

(A.6b) $$\frac{dy_{iNA}^*}{dK} = -\frac{1}{DET}\left[K\left(\mu_K^{iNA} a_{iA} - \mu_K^{iA} a_{iNA} - \mu_K^{iA} \beta K \psi'\right) + \mu_K^{iNA} P'\right].$$

Subtracting (A.6b) from (A.5a) it follows that:

(A.7a) $$\frac{dy_{iA}^*}{dK} - \frac{dy_{iNA}^*}{dK} = -\frac{1}{DET}\begin{bmatrix} K\left(\mu_K^{iA}\beta K\psi' - \mu_K^{iNA}(a_{iA} - b_{iA})\right) + \\ + \left(\mu_K^{iA} - \mu_K^{iNA}\right)P' + n\left(\mu_K^{iA} a_{iNA} - \mu_K^{iNA} b_{iA}\right) \end{bmatrix}$$

To find the sign of this difference, re-write n as n + (n-K) and use again $b_{iNA} = a_{iNA} + \beta K \psi'$. Then:

(A.7b) $$\frac{dy^*_{iA}}{dK}-\frac{dy^*_{iNA}}{dK}=-\frac{1}{DET}\begin{bmatrix} K\left(\mu_K^{iA}b_{iNA}-\mu_K^{iNA}a_{iA}\right)+ \\ +\left(\mu_K^{iA}-\mu_K^{iNA}\right)P^{'}+\psi(n-K)(a_{iNA}-\beta b_{iA})\end{bmatrix}$$

The three terms within square brackets are all negative for $K>K^{\circ}$ and $\beta<1$. This can be seen more easily by expanding (A.7b) as follows:

(A.7c)
$$\frac{dy^*_{iA}}{dK}-\frac{dy^*_{iNA}}{dK}=-\frac{1}{DET}\begin{bmatrix} K\left[\left(y^*_A-y^*_{NA}\right)\left(b_{iNA}b_{iA}-a_{iNA}a_{iA}\right)+\psi\left(b_{iNA}-\beta a_{iA}\right)\right]+ \\ +P^{'}\left(\mu_K^{iA}-\mu_K^{iNA}\right)+\psi(n-K)(a_{iNA}-\beta b_{iA})\end{bmatrix}$$

Hence:

a) $$\frac{dy^*_{iA}}{dK}-\frac{dy^*_{iNA}}{dK}>0 \text{ for } K\in[K^{\circ}, n];$$

b) As a corollary, given that $\frac{dy^*_{iA}}{dK}\geq 0$ for $K\in[K^{\circ}, K^A]$, the equilibrium output for non-signatories starts decreasing for a value of K such that $K^{NA}<K<K^A$ in the interval $[K^{\circ}, n]$.

When $\beta=1$, equation (A.7.c) becomes:

(A.8a) $$\frac{dy^*_{iA}}{dK}-\frac{dy^*_{iNA}}{dK}=-\frac{1}{DET}\begin{bmatrix} K\left[\left(y^*_A-y^*_{NA}\right)\left(b_{iNA}b_{iA}-a_{iNA}a_{iA}\right)+\psi\left(b_{iNA}-a_{iA}\right)\right]+ \\ +\left(a_{iNA}-b_{iA}\right)\left[\psi(n-K)-P^{'}\left(y^*_A-y^*_{NA}\right)\right]\end{bmatrix}$$

That is, by using (16):

(A.8b)
$$\frac{dy^*_{iA}}{dK}-\frac{dy^*_{iNA}}{dK}=-\frac{\psi}{DET}\left\{K\left[\frac{\delta}{P^{'}}\left(b_{iNA}b_{iA}-a_{iNA}a_{iA}\right)+\left(b_{iNA}-a_{iA}\right)\right]+\left(a_{iNA}-b_{iA}\right)\left(n-K-\delta\right)\right\}$$

It can easily be verified that the two terms within curly brackets are positive, so that, for $\beta=1$:

$$\frac{dy^*_{iA}}{dK}-\frac{dy^*_{iNA}}{dK}<0\,.$$

Q.E.D

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