DEPARTMENT OF ECONOMICS
UNIVERSITY OF CRETE
GRADUATE PROGRAM IN ECONOMIC THEORY AND POLICY

THE EVOLUTION OF VOLUNTARY ENVIRONMENTAL AGREEMENTS

Passa Constadina

Rethymno November 2003
A Thesis submitted in partial fulfilment of the requirements for the degree of MSc.
Supervisor: Xepapadeas Anastasios.

The Evolution of Voluntary Environmental Agreements

Abstract

This master thesis in the area of Microeconomic theory and Environmental Economics examines jointly the evolution of compliance to the environmental regulation and the evolution of realized emission stock in the industrial sector. The utilized evolutionary modeling process combines both the replicator dynamic equation, describing the proportion of firms that fulfill the regulation's provisions, and the emission stock dynamic equation. This dynamic system determines the equilibrium fraction of complying firms, as well as the corresponding equilibrium emission stock level, resulting both in the long-term period. The analysis indicates that the value and the structure of the auditing probability are of crucial importance for the resulting equilibrium outcome. It is evident that different assumptions about the auditing probability lead the dynamic system either in a monomorphic or polymorphic steady state. Moreover it is shown that under certain assumptions the resulting long-term critical point can either be a stable focus or stable node. Finally, it is shown that the regulator can lead the equilibrium outcome closer or even on the full-compliance steady state, through the appropriate design of the voluntary agreement and particularly through the legislatively imposed abatement.

Keywords: Voluntary agreements, abatement, regulation, compliance, legislation, replicator dynamics, auditing probability, polymorphic, monomorphic.

Rethymno November 2003

Table of Contents

List of Figures

The Evolution of Voluntary Environmental Agreements

I. Introduction

Pollution is the most typical example of negative environmental externalities, outlined in economic theory. It is widely known that such external effects lead to a sub-optimum resource-use and depletion of environment from a social viewpoint. Nevertheless theoretically there is room for a potential Paretian improvement, through the implementation of the appropriate environmental policies. However, experience indicates that the utilized traditional mandatory instruments, such as Pigouvian taxes, subsidies etc, have failed to serve efficiently the public demand for cleaner environment and rational use of natural resources. Their incapability to reverse the environmental degradation process, created the need for an environmental policy evolution and the development of new, more effective policy instruments.

Voluntary environmental agreements are a promising tool, attractive alternative to regulation since it is expected to increase economic, environmental effectiveness and social welfare (Segerson & Miceli, 1998). This instrument implies a new style of interaction between involved parties, based on the widely known Coase's idea of direct negotiations. However in real terms it is rather difficult to apply purely voluntary agreements and therefore this new environmental measure is based on a mix of voluntary and mandatory approaches (Segerson, 1998). Voluntary agreements usually are contractual commitments taken from polluting firms or industrial sectors, in order to improve their environmental performance in the time and ways outlined by a number of constraints and clear rules.

Even though the first voluntary environmental agreements were signed in 1960s the remarkable turn towards the particular instrument was realized in 1990s, supporting the superiority of the particular measure over the mandatory control and command measures. France and Japan were the first countries that undersigned negotiated agreements at 1971 and 1964 respectively. Particularly, in France the cement industry obliged itself to comply with stricter air pollution standards as the act of 1960 required. The goal was achieved progressively in order to allow firms invest on a greater scale, while the 10% of their investment actions was subsidized by the Ministry of Environmental Issues (Šauer & all). Recent research underlines that in European Union have been undersigned more than 300 voluntary agreements, on contrast to Japan that counts 30.000 agreements concluded mainly in local level.

The majority of economic research has focused on the applicability of voluntary agreements in the short-term period and mostly in the management of point source (PS) pollution problems, which are based on the assumption of perfect information. Notable example is the paper of Segerson & Miceli (1998) where they have identified the conventions that guarantee and affect the final implementation of voluntary agreements in the short-term period. Moreover, the paper of Brau & all (2001) has well defined the conditions under which a group of firms has an incentive to sign an agreement even in the presence of free-riding by other firms in the industry, as well as the features that voluntary agreement ought to possess in order to induce all the firms to comply with the regulator's provisions. Finally, Segerson (1998) determines the applicability conditions of voluntary agreements in a static non-point source pollution problem, characterized by informational constraints.

Nevertheless, according to Šauer & all (2001) it is essential to evaluate the environmental efficiency of voluntary agreements in a dynamic perspective, since technical advancements may shift the environmental quality optimum at the macroeconomic level. Furthermore, in this work is also underlined the necessity to evaluate the macroeconomic effects of negotiated contracts on price level and inflation, employment and unemployment, economic growth, investments and foreign trade. However, little research work has been done on the evolutionary applicability of voluntary agreements in pollution control problems. Thus little is known about the factors that influence and guarantee the sustainability of voluntary contracts in the long-term period and furthermore affect their applicability and efficiency.

In this relatively new research area characteristic are the attempts of Ostrom (1990) and Sethi & Somanathan (1996), who both model the evolution of social norms in environmental and source management problems. Recently A. Xepapadeas (2003) models jointly the evolution of compliance to regulation and the evolution of the common pool resources (CPR) in the context of an evolutionary process emerging from the combination of replicator dynamics, which describe the adoption of harvesting rules, with resource stock dynamics. This evolutionary approach characterizes the emergence of steady-state equilibrium harvesting rules or compliance levels under regulation, and the corresponding behavior of the steady-state equilibrium resource stock, suggesting that the coexistence of both cooperative and non-cooperative rules under regulation is possible.

In the same context the present master thesis models endogenous compliance for voluntary agreements using an evolutionary approach, determined by replicator dynamics (Gintis H., 2000). Particularly it examines jointly the evolution of compliance to the environmental regulation and the evolution of realized emission stock in the industrial sector. The utilized evolutionary modeling process combines both the replicator dynamic equation, describing the proportion of firms that fulfill the regulation's provisions, and the emission stock dynamic equation. The solution of the particular dynamic system determines the equilibrium fraction of complying firms, as well as the corresponding equilibrium emission stock level, resulting both in the long-term period under different assumptions about the behavior of a certain parameter of the problem.

The analysis of the particular dynamic system indicates that the value and the structure of the auditing probability are of crucial importance for the resulting equilibrium outcome. It is evident that different assumptions about the definition of the number of random inspections lead the dynamic system either in a monomorphic or polymorphic steady state. It is also shown that under certain assumptions the resulting long-term critical point can either be a stable focus or stable node. Moreover, it is shown that the dynamic system can be trapped in a bad equilibrium and in this case it is impossible to restore the system in an environmental friendlier state. Finally, it is shown that the regulator can lead the equilibrium outcome closer or even on the full-compliance steady state point, through the appropriate design of the voluntary agreement and particularly through the legislatively imposed abatement.

II. Voluntary Environmental Agreements: a Review

Pollution is the most typical example of negative environmental externalities, outlined in economic theory. It is widely known that such external effects lead to a sub-optimum resource-use and depletion of environment from a social viewpoint. Nevertheless theoretically there is room for a potential Paretian improvement, through the implementation of the appropriate environmental policies that may even lead in the socially-desirable environmental quality level. At the beginning environmental policy relayed on polluter pays principal and based mostly on mandatory instruments such as Pigouvian taxes, subsidies etc. However, experience indicates that these measures imply high costs and lack of flexibility, making impossible the adequate internalization of external damage into polluters' behavior. Their incapability to reverse the environmental degradation process, created the need for an environmental policy evolution and the development of new, more efficient policy instruments.

Indeed the environmental policy was re-engineered and the instrument of voluntary approaches seems to be the answer to the increasing public environmental demand and the necessity to face degradation problems in a more structured and long term way. Particularly, a swift from polluter pays principle to a precautionary and shared responsibility principle took place, where all social forces and all activity fields participate in the prevention and maximum possible reduction of environmental impacts (Pesaro, 2001). Moreover, a move was realized from direct regulation and centralized environmental policy, to a participatory and decentralized policy that focuses mostly on prevention goals and voluntary actions undertaken by economic subjects in terms of self-regulation and voluntary adjustment to better environmental performance standards.

The use of voluntary approaches to environmental protection appears to be an attractive alternative to regulation. Such approaches are often a "softer" form of regulation and can be broader and more encompassing than mandatory requirements. In the relative economic literature three basic categories of voluntary approaches are met: Unilateral Commitments by firms and industries, Public Voluntary Programs, Negotiated Agreements (Šauer P. and all, 2001).

The unilateral commitments are also known as "self-regulation", since they are environmental improvement programs undertaken by firms themselves and communicated to their stakeholders (Brau & all, 2001). Literally, polluting firms prepare and voluntarily adopt environmental programs, at which they have defined environmental goals themselves and have stated measures that lead to their achievement. It is possible that they have also authorized a third party to monitor and conflict-resolution, in order to increase the credibility and environmental effectiveness of their commitment. Notable is the example of the Canadian Chemical Producer's Association that adopted the "Responsible Care" unilateral commitment due to the decreasing public trust on chemical industry and the danger of stricter regulation (Šauer et all). Similar commitments are the 3M's 3P programme, Dow Corporation's WRAP and CMA's Responsible Care programme (Dawson and Segerson, 1999).

In the second category are met programs developed by some public bodies and to which polluting firms can only agree with (Brau & all, 2001). Actually, firms must agree with the program's certain rules since they influence their activities, technology or management. These rules have been prepared in advance by public institutions and incorporate the program characteristics, the requirements for individual participation, measures to be undertaken by firms, ways of monitoring commitment and means of evaluating the results. Moreover, public institutions provide supplementary funds for science and research, technical aid, as well as rights to use an ecological logo or certification idol, in order to develop the necessary environment that lead to a broader and more efficient implementation of such programs. Notable examples are the programs of environmental management systems certification standards, EMAS and ISO 14000 respectively (Dawson & Segerson, 1999).

Finally the negotiated agreements, or else known as voluntary environmental agreements (VAs), are based on a new style of interaction between involved parties and imply a bargaining process that under some conditions can end up with the signing of an agreement. They are contractual agreements between a regulatory body and a firm or a group of firms, which include a goal, a schedule and other conditions necessary to reach the expected results. Such contracts are usually commitments taken from polluting firms or industrial sectors, in order to improve their environmental performance in the time and ways outlined by a number of constraints and clear rules. Legal obligations might be also included and operate only if the agreed goal is not fulfilled or the agreement is not undersigned. Characteristic examples of such negotiated agreements are the EPA's Project XL and the French agreement on the treatment of *End*-of-life Vehicles (ELV's) (Dawson and Segerson, 1999).

The previous categorization of voluntary approaches was based mainly on the degree of public intervention, meaning mostly the degree of authority's impact on a certain hierarchical level of public administration. Nevertheless, according to Šauer P. & all (2001) the voluntary approaches can be further differentiated pact and with other criteria such as the level of legal obligation, agreement initiator, the sanction types, their objective etc.

Usually voluntary approaches are differentiated according to their objective. There are "target-based agreements", which are based on exactly specified[1] goals in the area of environmental protection. Such an agreement was undersigned in 1995 by a group of German industries associations, which aims to reduce CO_2 emissions by 20% relatively to the 1999 baseline by 2005 (Segerson, 1998). Moreover, in economic literature are met voluntary approaches that either establish less precise environmental targets, target directly toward technological progress in the area of cooperation in research and development or merely obligate participating firms to provide information relatively to their effects on the environment. Finally, there are "implementation agreements", which aim to determine the means that develop a consensus with previously established environmental policy goals.

Furthermore, voluntary approaches can be further categorized according to the level of openness toward third parties, the agreement initiator that can be an authority, polluters and non-governmental organizations, and the sanction types that operate if signatory firms fail to fulfill the agreement's provisions and can be financial, moral or even different means of regulation. Moreover, the level of legal obligation that the fulfillment of the agreement may imply to signatory firms can be used as another differentiation criterion. Characteristic are the examples of negotiated agreements undersigned in Netherlands, where the majority of voluntary contracts have civil-law characteristics. This implies that if a participating firm fails to fulfill the agreement's goals then it is responsible in front of a civil court (Šauer P. et all, 2001). It is notable that the 90% of the 100 agreements, pursuant due to the Dutch National Environmental Policy Plan, where obligatory.

Finally experience indicates that voluntary approaches can be further separated relatively to their application level. Particularly, they are differentiated to firm-specific, industry-wide, national, federal[2] or regional approaches. Firm-specific approaches are concluded between local authorities and individual firms, and are capable to push local systems to develop actions and solutions for specific needs, while industry-wide approaches are concluded between governments and industries or associations, and involve an environmental target for the whole industry. On the other hand, there are regional voluntary approaches since every geographic region develops its own model that is strongly characterized by the territorial peculiarities. Regional

[1]These goals are quantified.

[2] For detailed presentation of the characteristics of international voluntary agreements in practice, see Table 1 at the Appendix.

applications are more likely than industrial applications, since the design and implementation capability appears to be greater when actors and problems occur on a restricted area. [3]

Nevertheless, the most common case of voluntary approaches is the voluntary environmental agreements. One theoretical way out is the Coase's idea of direct negotiation between polluters and those harmed[4]. Such purely voluntary agreements are based on certain conditions such as zero transaction costs, well defined ownership rights toward environmental goals, facilitated access to information and of course on the willingness of involved parties to negotiate in order to limit the unfavorable external effects (Šauer P. & all, 2001). Under these conditions the negotiation always leads to the same result and make it possible for the parties to improve their respective situations, whether the polluter is liable for the external effects or not. However, in real terms it is to difficult to identify the ownership rights, contract and organize interest groups and carry out such negotiations to the very end.

According to Segerson (1998) neither purely voluntary environmental agreements nor purely mandatory approaches seem to offer a desirable solution to excess pollution. Therefore it seems rather unlikely that negotiated agreements will improve the environmental quality as an independent policy instrument. Nevertheless, there is an alternative role for voluntary and mandatory approaches, to control pollution as complementary instruments used together rather than as substitutes used in isolation. Indeed this new environmental policy instrument is based on a mix of negotiation between authority and polluters and application of economic tools of environmental policy. The combined use of voluntary and mandatory tools, guarantee that the polluting agents will reduce their economic residuals to a desirable level due to the economic interests that appear.

Particularly, authorities[5] utilize instruments such as financial inducements[6], technical aid, or even a law for using ecological logos, in order to promote a socially effective allocation of limited resources and environmental friendly behaviour from polluters' side. Such contributions can be temping for some firms, since they create a surplus over integrated costs of environmental protection and "encourage" participation in a voluntary agreement. Such agreements are mostly an instrument that formulizes an exchange. This method is known as "carrot" approach and is mostly based on positive incentives. Characteristic example is the U.S. Conservation Reserve Program, which utilizes cost-sharing and other financial inducements in order to reduce agricultural pollution and relies on voluntary participation in soil conservation and erosion control (Segerson and Miceli, 1998).

However, the participating incentives can not be always positive. The authority may promise not to establish a new regulation[7] as long as the agreement is undersigned and its provisions are fulfilled. Notable example is the Project XL that exempts firms from certain mandatory requirements if they exceed environmental protection goals through other means. Literally, authorities "obligate" polluters to adopt

---

[3] Notable is the example of "Part for Energy and Environment" agreement that was signed in national, regional and local level, as well as it was signed by individual economic actors on particular goals (Pesaro, 2001).

[4] These voluntary approaches are also called: private environmental agreements, because they are concluded between the polluters and those harmed.

[5] Authorities are institutions, not necessarily governmental institutions, which induce participation in environmental voluntary environmental agreements.

[6] These financial inducements can be total-cost or cost–sharing subsidies.

[7] Such as taxes, fees and environmental limits.

environmental-friendly practices by threatening a harsher outcome, through the implementation of mandatory restrictions. This method is known as “stick” approach, since authority threatens to impose mandatory controls such as penalties, taxes[8] and other sanctions if the agreement target is not met or the agreement is not undersigned. In this case voluntary agreements are considered to be an effective instrument that forces parties to “accept” their responsibilities for the functioning of the new action mechanisms (Segerson & Miceli, 1998).

Obviously, in this case the use of the term “voluntary” is not that successful since this term embodies the free will of firms to commit themselves to the agreement. Experience indicates that such instruments are utilized mostly for the control of non-point pollution problems, merely in the industrial sector and seldom in the agricultural sector, with recent applications the Clean Water Act and the Clean Air Act that are based on a regulatory approach to pollution control (Segerson, 1998). There are plenty notable examples of “voluntary” agreements following the stick approach. Nevertheless, characteristic applications are the Superfund Act of 1986 and the Clean Air Act (CAA) Amendments of 1990, which relayed on the threat of liabilities and future compliance costs in order to induce firms to internalize the costs of their current toxic pollution (Khanna & Damon, 1999).

In this point it is important to mention that voluntary agreements can be feasible even in the absence of participation incentives. Signatory firms that are in close contact with final consumers, such as a highly brand identity, have strong dependence on their public image and therefore it is expect to be benefited more from purely agreements. Particularly, such agreements are expected to improve firm’s public image with respect to environmental issues and increase consumers’ goodwill, leaving potential room for an increase in sales (Khanna & Damon, 1999). Moreover, the pollution reduction agreements are considered as a cooperative strategy that guarantees long-term benefits since they may increase investors’ confidence towards signatory firms. Firm’s commitment to reduce pollution ahead of time by flexible methods can be perceived as a sign that it is gaining a strategic advantage over its competitors.

The last decades there is a remarkable turn towards the instrument of voluntary environmental agreements, strongly connected with their advantages over mandatory tools. Particularly, such agreements offer a potential for greater flexibility, since they allow individual firms to choose the means by which they will achieve the fulfilment of the determined environmental target (Segerson, 1998). The fact that these negotiated contracts do not dictate the implementation of a particular technology, lead to higher solution variability since it permits individual firms to correspond rapidly and adjust their solutions to the timely changes of technical and economic parameters (Šauer P. & all, 2001). This sort of flexibility encourages creativity, which can also lead to technical innovations and information dissemination, dealing with alternative techniques of pollution reduction.

Under the voluntary agreements a demand for new and less costly solutions for environmental protection is created. The new solutions not only reduce pollution but also promote technical progress that can reduce environmental compliance costs, administrative costs, as well as transactions costs associated with the preparation, conclusion and inspection of the concluded agreement. Therefore negotiated voluntary agreements are more cost effective since they deter varying individual

[8] There are cases, where if a VA is signed then firms will pay a lower tax. This might take place when a legislative tax already exists.

marginal abatement costs and lead to socially less expensive solutions for given environmental problems. Furthermore, firms in order to control pollution use their inputs more efficiently, increasing their productivity and reducing input costs. As a consequence there are expenses savings on materials, energy, wages, lower risks and possibly better credit ratings through the participation in an agreement (Khanna & Damon, 1999).

The negotiation processes can also lead to a collective understanding of environmental problems and a mutual responsibility from polluters' side, since they require positive actions and not passive reactions to instruments implemented by authorities. Such voluntary actions influence consumers' choice regarding a range of products and lead to the substitution of older, less environmental friendly products with new products that process desirable characteristics in environmental terms. Moreover, agreements can alleviate the economic impact of environmental laws on heavily affected sectors and can reach beyond the scope of generally established legal regulations in environmental protection (Šauer P. and all, 2001). Finally, voluntary agreements may speed up the achievement of established goals in a way that other approaches cannot, due to decreased negotiation and implementation lags.

Unfortunately, voluntary agreements present and drawbacks. The main and most important disadvantage is that there is room for "free riding" behavior. Experience indicates that in an industry-wide agreement individual firms have an incentive to rely upon other firms to carry out the collective emission target, without cutting their emissions. Firms either decide not to participate in the fulfillment of the established goal from the beginning (ex-ante) or they accept the agreement but do not fulfill its provisions at the very end since they do not anticipate a long-term cooperation with the agreement partners (ex-post). Moreover, if the regulation is set industry-wide then non-complying firms reap the benefit of the avoided regulation without incurring the cost of fulfilling the agreement's provisions. Such free riding behaviors can lead to a failure of an agreement before the potential benefits are realized.

In the case of pure public goods voluntary agreements fail to be signed since all the firms are benefited in the same amount, due to the characteristics of no rivalry and no excludability that the agreement's benefits possess (Brau & all, 2001). Furthermore voluntary agreements may make it impossible for some firms to enter the market or prohibit a third party from entering the system or even drive a product out of the sector gradually. This implies that voluntary contracts may cause disturbances in the conditions of economic competition. Particularly, in 1977 European Committee evaluated 20 instances of that kind (Šauer P. and all, 2001). Moreover, inadequate clarity of the negotiated agreements decreases their trustworthiness in the eye of the public, making difficult the fulfillment of an agreement. Nevertheless, trustworthiness can be positively affected by the establishment of an independent party that monitor and report to the public the data concerning fulfillment.

Recent experience indicates that the implementation of voluntary agreements faces difficulties. Notable is the Italian example of the "Part for Energy and Environment" negotiated agreement, which shows that the first obstacle to an adequate use of such tools is the actors' difficulty to interact in this new way and understand the conditions and constraints that such a system implies. Moreover, difficulties appear when private participants are fragmented, loosely organized and very heterogeneous, implying that there is a big variety of interests among them. The probability that voluntary contracts will be signed is expected to be low, if the complexity degree of the situation is too high and there is lack of adequate information for the development of concrete actions in time. Finally, difficulties appear if there is a little coherence between the content and commitments foreseen by the agreements, implying that the targets must be developed on the basis of real nature and realistic capabilities of the parties.

According to the relative literature the applicative effectiveness of voluntary agreements can be improved if they demonstrate some particular features. First of all negotiated agreements should be written, consensual and include implementation deadlines. The wording of the context of a reference, starting conditions, objectives and proposed means for their achievement must be clear, plausible and unambiguous (Šauer & all, 2001). Furthermore, the agreement's objectives must be determined on a consensual basis and be quantified, while the legal nature of the instrument binds the signatory parties to their commitments that should be doable. The implementation of a clear mechanism of sanctions, which operates when firms fail to fulfill the agreement's provisions, motivates the willingness of industrial firms to realize the established environmental goals.

An efficient agreement should take into account all subjects influenced by the implementation of the agreement and satisfy all parties in three dimensions: interests, process and the personal dimension (Šauer & all, 2001). Additionally, it should not create conflicts and should respect known and available data, as well as existing conditions. Negotiation process should be characterized from transparency and accessibility to information concerning all the environmental performance. Environmental goals should be formulated with closer attention in order to increase ecological effectiveness, and moreover should be defined according to the national plan of ecology policy, otherwise there is a potential be underestimated.[9] It is possible to improve the quality of the entire process by including third parties in the goal establishment step, as a type of control and checking mechanism, for the control of activity phases and for the checking of the achievements of targets.

III. The Industrial Model

Assume an industrial sector constituted with $i = 1, 2,\ldots, n$ small firms. Firms operate under competitive conditions and impose their economic residuals to the environment, leading to sub optimal situations in terms of social welfare. To deal with this problem the regulator forms an emission target for the whole industry and offers the industry an opportunity to achieve it voluntarily. Particularly he makes a "take-it-or-leave-it" offer of a specified abatement level α_v, the implementation of which guarantees the adequate internalization of the environmental externality, while simultaneously he threatens to impose legislatively the abatement level α_L to those firms that deny to fulfill the provisions of the proposed voluntary agreement.

However, it is known that the large number of emission sources make impossible the simultaneous monitoring of all these small firms, since this would be prohibitely costly for the regulator.[10] Therefore it is preferable for him to make a number of random inspections and control only a proportion of firms each time period. As a consequence the legislation mandate is enforced, if and only if during the random inspections firms are caught not to comply with the agreement. Therefore non-complying firms know that there is a probability p, under which they can be caught by the regulator and finally be liable to the legislation's norms. This probability is so-called auditing probability and can either be fixed or dependent on global variables such as the total emission stock and the existing compliance proportion.

[9] This is probable when the environmental targets are established by the industrial sector itself.
[10] The problem has the main characteristics of a non-point source pollution problem (NPS).

Nevertheless, a voluntary agreement of that kind does not guarantee that the emission target will be achieved at the very end. It is possible that some complying firms do not use the voluntary abatement level α_v, even though they have installed it, either because they are not able to cover its operating cost or they do not have the appropriate staff and knowledge to operate efficiently such equipment. Therefore, the regulator ought to include an additional condition in the voluntary agreement, in order to ensure that firms will not only install but also use their abatement in the best feasible way. This can be achieved through a collective penalty[11], paid by the entire industry whenever its total emissions exceed the determined environmental target.

It is known that the regulator's objective is to maximize net social benefit (*NSB*), either through a voluntary agreement or a legislative mandate. In the first case the net social benefit is equivalent to the following expression:

$$NSB_v(\alpha_v) = B(\alpha) - TC_v(\alpha_v) \qquad (1)$$

The term $B(\alpha)$ defines the social benefits of abatement and is considered to be independent of the source that imposed the observed abatement level. On the other hand, the term $TC_v(\alpha_v)$ denotes the total social costs that the voluntarily abatement level implies and contains both the compliance and transaction cost. Moreover, the first order condition of this expression, defined as $B'(\alpha) - TC_v'(\alpha) = 0$, determines the abatement level α_v^* that maximizes net social benefits under the agreement. It is important to mention that this abatement level is the first best level that guarantees the maximum possible environmental protection.

In a similar way the regulator, or alternatively a legislative body, determines the abatement level α_L^* that maximizes the expected net payoffs under the utilization of a legislation mandate. The term "expected" is used since the final implementation of the legislative abatement level is uncertain and takes place under a probability *p* if and only if non-complying firms are traced. Particularly, the expected net social benefit is equivalent to the following expression:

$$pNSB_L(\alpha) = p[B(\alpha) - TC_L(\alpha)] \qquad (2)$$

Where the term $TC_L(\alpha)$ defines the total social costs acquired under the legislative abatement level. Moreover, the legislative abatement α_L^* solves the relative first-order condition $B'(\alpha) - TC_L'(\alpha) = 0$.

Both α_v^* and α_L^* maximize social welfare, but under different circumstances. Nevertheless, according to K.Segerson & all (1998) the abatement level α_v^* is always greater than the expected abatement level α_L^*, since both the total and marginal social costs of abatement $TC'(\alpha)$ are higher under the legislative approach. This implies that $TC_V(\alpha) < TC_L(\alpha)$ and $TC_V'(\alpha) < TC_L'(\alpha)$ for all the abatement levels. Particularly, it is assumed that both the total and marginal transaction as well as compliance social costs[12] are lower under the voluntary agreement than under the legislative mandate, since the agreement implies reduced conflict and reliance on formal legal procedures and increased flexibility in determining the means by which the environmental goal is achieved.

[11] This fine gives firms the essential motivation to use their abatement in the best feasible way.
[12] In this case the transaction costs are borne both by firms and the regulator, while the compliance costs are borne only by firms.

On the other hand, firms' objective is to minimize their respective transaction and compliance costs, defined in the relative economic literature as $C(\alpha)$. Under these conditions firms have to decide whether or not it is profitable to comply with the regulator and fulfill the voluntary agreement's provisions. In this point it is important to mention that firms may adopt the non-compliance behavior from the initial period t_o (ex-ante free riders) or after a time period *t* (ex-post free riders) even though they appear to have undersigned the agreement[13].

In the first case firms know that if they accept the offered agreement, implement voluntarily the proposed abatement level α_v and conform to the emission standards, then the legislative threat will not be imposed to them and their functional costs will be equal to $C_V(\alpha_V)$. However, there is a probability *q* that the industrial sector, as an entity, fails to achieve the environmental goal e^*_{target}. In that case all the firms face a fine *F* that is proportional to the excessive pollution, produced above the determined emission target.

Thus the firms that undersign the voluntary agreement and comply with its provisions face the following cost function:

$$C_v\!: \; C_V(\alpha_V) + qF(\sum_{i=1}^{n} e_i(\alpha_i) - e^*_{target}) \qquad (3)$$

The term $\sum_{i=1}^{n} e_i(\alpha_i)$ defines the total amount of emissions released in the industrial environment under the various realized abatement decisions. It has to be defined that if the industrial sector succeeds to achieve the environmental target or even reduces the total emissions' amount under this critical level, then there is no tax either reward from the regulator's part. This implies that if $\sum_{i=1}^{n} e_i(\alpha_i) \geq e^*_{target}$ then $F = 0$. Henceforth the term Δe is utilized in order to symbolize the excessive pollution $\sum_{i=1}^{n} e_i(\alpha_i) - e^*_{target}$ for convenience.

In the second case firms refuse to comply with the proposed voluntary agreement, either ex-ante or ex-post, and implement the abatement level α_o that minimizes their operational costs[14]. Firms hope that the regulator will not "trace" them doing so and therefore they will not be subject to the provisions of a potential legislation. In this case their operational costs are equivalent to $(1-p)C(\alpha_o)$, since *p* is a probability to be caught and punished. On the other hand, if during the random inspections they are caught then their expected costs under the legislative threat are equal to $pC_L(\alpha^*_L)$.

Moreover, firms are debited a probabilistic fine *F* if the industrial sector fails to fulfill the predetermined environmental target. Consequently the firms that do not comply with the voluntary agreement's rules have the following cost function:

$$C_c\!: \; pC_L(\alpha^*_L) + (1-p)C(\alpha_o) + qF\Delta e \;\rightarrow\; C(\alpha_o) - p[\,C(\alpha_o) - C_L(\alpha^*_L)\,] + qF\Delta e \quad (4)$$

Where the expression $[\,C(\alpha_o) - C_L(\alpha^*_L)\,]$ is negatively defined since the inequality $C_L(\alpha^*_L) > C(\alpha_o)$ is valid. Literally this term defines the excessive cost that the firms have to bear when the regulator catches them not complying with the offered

[13] As Šauer et all (2001) underline in their work.

[14] This implies that α_o: *min* $C(\alpha)$.

agreement. It is an additional cost since the non-complying firms have to cover the difference between the cost minimizing abatement α_o and the legislative abatement α_L^*.

In this point rises a reasonable question: What does constitute the potential legislative punishment? It has been already mentioned that the voluntary agreement implies lower transaction and compliance costs for society compared to the relative costs the legislation mandate does. Nevertheless, in the same paper Segerson & Miceli (1998) suggest that the same applies and for the transaction and compliance costs $C(\alpha)$ borne exclusively by firms. As a consequence the hypothesized cost advantage of voluntary agreements implies that the inequalities $C_V(\alpha) < C_L(\alpha)$ and $C'_v(\alpha) < C'_L(\alpha)$ are valid for all the feasible abatement levels.

It is obvious that the polluting firms decide to comply with the voluntary agreement, if and only if the operating costs C_v under the agreement are less or even equal to the operating costs C_c that the "non-compliance" behavior implies. In this case the following inequality should be valid:

$$C_V(\alpha_V) + \Delta e \leq C(\alpha_o) - p[C(\alpha_o) - C_L(\alpha_L^*)] + qF\Delta e \qquad (5)$$

Additionally the relative literature underlines that the inequality $\alpha_V^{\min} \leq \alpha_V^{\max}$ must hold, if the voluntary agreement is expected to be one of the potential equilibrium outcomes. Where the term $\alpha_V^{\min}$ is the minimum abatement level that the regulator is willing to offer under the voluntary agreement, while the term $\alpha_V^{\max}$ is the maximum abatement level that the firm is willing to accept under the proposed agreement.

However it should not be taken for granted that the proposed voluntary abatement is always the first-best level α_V^*. It is known that the allocation of bargaining power between the regulator and the firms, or even a firm representative, affects the existing value of the voluntary abatement α_V. Thus under the assumption that the regulator possesses all the bargaining power and that the inequality $\alpha_V^{\min} < \alpha_V^* < \alpha_V^{\max}$ holds, the proposed abatement is the first-best level α_V^*.[15] However, if this inequality $\alpha_V^{\min} < \alpha_V^{\max} < \alpha_V^*$ is valid then the regulator proposes the maximum abatement level that the firms are willing to accept ($\alpha_V^{\max}$), that is obviously less than the first best level and uncertain whether it is higher or lower than the level imposed legislatively.

On the other hand, if the firms possess the bargaining power then they choose the minimum feasible abatement level $\alpha_V^{\min}$, in order to meet the environmental standards voluntarily. Particularly, this voluntary abatement level is less than the first best level α_V^* and legislatively imposed abatement level α_L^*, since the inequality $\alpha_V^{\min} < \alpha_L^* < \alpha_V^*$ holds, and it is reasonable that firms implement the cost minimizing abatement level α_o. Finally if the bargaining power is shared between the two negotiated parties, then the voluntary abatement level is be less than the first best level and moreover there is a possibility that it is less than the legislative abatement α_L^*.

Nevertheless, this analysis considers that the regulator has all the bargaining power and does not examine the rest cases at all. Furthermore it considers that the voluntary abatement level α_V is greater or even equal to the legislatively imposed abatement

[15] This is the case of supercompliance, under the assumption that the firms comply with the agreement, since the implement more abatement than they are willing to do.

level α_L^* that optimizes the social welfare, thus the inequality $\alpha_o < \alpha_L^* \le \alpha_V$ holds always in this master thesis. Finally no statement is made whether the voluntarily implemented abatement level α_V is the first best level or not, since this thesis does not intent to examine the voluntary agreement's ability to achieve the maximum feasible environmental protection.

IV. The Replicator Dynamic

Assume that at a given time *t* the industrial sector consists of two groups of firms, the complying firms that undersign the offered agreement and the non-complying firms that refuse to cooperate with the regulator ex-ante or ex-post. Particularly, $x_V(t)$ is the proportion of polluting firms that comply with voluntary agreement's rules and $x_N(t)$ is the remaining proportion of firms that do not implement the socially desired abatement α_V and face the potential legislation. This population has only these two pairs of players, so it holds that:

$$x_V(t) + x_N(t) = 1 \;\rightarrow\; x_N(t) = 1 - x_V(t) \qquad (6)$$

However, there is a positive probability *αdt* that in every time period *dt* each firm switches its strategy if it learns and perceives as lower the operating costs *C*(*α*) of a randomly chosen firm, following another strategy. Particularly the firm *i* that did not comply with the voluntary agreement in time *t*, decides to change its strategy and finally fulfill the agreement's provisions if its operating cost C_N^i is higher than the relative cost C_v^j of a complying firm. It is important to mention that there is imperfect information about the difference in the operating costs of the two strategies. Therefore it is logical to assume that the probability *αdt* increases as the difference between the costs gets larger.

As a consequence the probability that a non-complying firm changes its strategy and adopts a "cooperative" behavior, after learning the operating costs of one of its opponents, is given by:

$$P_{NV}^t = \begin{cases} \beta\left(C_N^t - C_V^t\right), when\, C_N^t > C_V^t \\ 0 \qquad\quad , when\, C_N^t < C_V^t \end{cases}$$

Thus the expected proportion of firms that decide to comply with the regulator and undersign the voluntary agreement in period *t* + *dt* is defined as:

$$\mathrm{E}x_V^{t+dt} = x_V^t + \alpha dt x_V^t \sum_{j=1}^{n} x_N \beta\left(C_N - C_V\right) \quad \text{or}$$

$$\mathrm{E}x_V^{t+dt} = x_V^t + \alpha dt x_V^t \beta\left(\overline{C}^t - C_V^t\right) \qquad (7)$$

Where $\overline{C}^t$ is the average cost for the whole population in time *t* and is equal to:

$$\overline{C} = x_V\{C_V(\alpha_v) + qF\Delta e\} + (1 - x_V)\{C(\alpha_o) - p[C(\alpha_o) - C_L(\alpha_L^*)] + qF\Delta e\} \quad (8)$$

Under the assumption that the industry consists of a large number of firms, the expression $\mathrm{E}x_V^{t+dt}$ can be replaced by x_V^{t+dt}. Furthermore if we subtract from both sides the term x_V^t, divide by *dt* and finally take the limit as $dt \to 0$, we get an expression that describes the behavior of the fraction x_V over time. This equation is known as the replicator dynamic and has the following form:

$$\dot{x}_v = \alpha\beta x_v\left[\overline{C} - C_v\right] \qquad (9)$$

The replicator dynamic equation indicates that the frequency of the compliance strategy increases whenever the operating cost C_V under the compliance strategic behavior is underneath the average industrial cost $\overline{C}$. Nevertheless it would not be wrong to assume that $\alpha\beta = 1$, so the replicator dynamic can be rewritten as:

$$\dot{x}_v = x_v\left[\overline{C} - C_v\right] \qquad (10)$$

In this specific case it has the following final form:

$$\dot{x}_V = x_V\left[x_V\{C_V(\alpha_V) + qF\Delta e\} + (1 - x_V)\{C(\alpha_o) - p\left[C(\alpha_o) - C_L(\alpha_L^*)\right]\} - C_V(\alpha_V) - qF\Delta e\right]$$

$$=> \dot{x}_V = x_V(x_V - 1)\{C_V(\alpha_V) - C(\alpha_o) + p\left[C(\alpha_o) - C_L(\alpha_L^*)\right]\} \quad \text{or}$$

$$\dot{x}_V = x_V(x_V - 1)\{C_V(\alpha_V) - C(\alpha_o) - p\left[C_L(\alpha_L^*) - C(\alpha_o)\right]\} \qquad (11)$$

It is noticeable that the probabilistic fine F does not affect the evolution of the proportion x_v over time. Nevertheless, this should not be surprising since both groups of firms are overloaded with the same sum and therefore on the average the fine's influence is eliminated.

In this point it is really tempting to determine the potential equilibria that might result, under the existing conditions. Particularly in the long-run the industrial sector might balance in a polymorphic or monomorphic critical point. A steady state is so-called polymorphic if a heterogeneous strategic behavior is evolutionary sustainable in the long-term period. This implies that only a proportion of firms comply with the agreement, while the remaining proportion denies the regulator's proposal. On the other hand the long-term equilibrium is monomorphic if all the firms follow the same strategy and adopt a homogenous behavior. This implies that either all the firms comply with the agreement's provisions or that they all refuse to fulfill the agreement's provisions ex-ante or ex-post.

V. The Evolutionary Equilibrium

In the derivation of the replicator dynamic equation we did not make any particular assumption about the auditing probability p. It could be said that it was treated as if it was fixed and known to the polluters. Nevertheless this can not be always valid, since the probability value can be alternatively set according to the existing circumstances in the industrial sector. Particularly the probability that a non complying firm is caught and thus punished legislatively, can be either dependent on the observed emission stock S_e, the observed proportion of complying firms x_V or even the combination of these two global variables.

Therefore it is interesting to examine how these alternative variable dependent auditing probabilities affect the resulting evolutionary stable equilibrium.

Case 1: Fixed auditing probability p

Assume that the legislative probability is exogenous determined and fixed during each time period. This implies that the regulator announces a specific number of random inspections and sticks to it. Therefore the firms know exactly the probability $\overline{p}$ under which they may pay the extensive cost $C_L(\alpha_L^*) - C(\alpha_o)$, if they are caught disobeying the voluntary agreement's provisions. Thus based on this knowledge they determine their strategy over time.

Under this assumption the replicator dynamic is defined as:

$$\dot{x}_V = x_V(x_V - 1)\{C_V(\alpha_V) - C(\alpha_o) - \overline{p}\left[C_L(\alpha_L^*) - C(\alpha_o)\right]\} \qquad (12)$$

In order to determine the relative steady state points we set $\dot{x}_V = 0$. In this case only two equilibria have been found to satisfy this condition:

→ $x_V^* = 0$ and all the firms refuse to cooperate with the regulator and do not undersign the voluntary agreement.

→ $x_V - 1 = 0$ => $x_V^* = 1$ and all the firms comply with the agreement.

Moreover, there is a fixed probability value that makes the last expression zero and consequently satisfies the condition $\dot{x}_V = 0$:

$$\rightarrow C_v(\alpha_V) - C(\alpha_o) - p[C_L(\alpha_L^*) - C(\alpha_o)] = 0 \Rightarrow \hat{p} = \frac{C_v(\alpha_V) - C(\alpha_o)}{C_L(\alpha_L^*) - C(\alpha_o)}$$

Where $\hat{p} < 1$ since $C_v(\alpha_V) - C(\alpha_o) < C_L(\alpha_L^*) - C(\alpha_o)$. This is a critical probability level that plays important role to the long term sustainability of these two equilibria, as it is seen below.

In this point it is essential to determine the type of the equilibrium, to define which of the fixed points is stable and which is unstable in the long run. For that reason the derivative of the replicator dynamic equation with respect to the fraction x_V, is taken:

$$\frac{d\dot{x}_V}{dx_V} = (2x_V - 1)\left\{C_V(\alpha_V) - C(\alpha_o) - \bar{p}\left[C_L(\alpha_L^*) - C(\alpha_o)\right]\right\}$$

However, the sign of the last expression $\Omega = \left\{C_V(\alpha_V) - C(\alpha_o) - \bar{p}\left[C_L(\alpha_L^*) - C(\alpha_o)\right]\right\}$ is uncertain and strongly dependent on the auditing probability value. Furthermore, it is obvious that the existing probability value p defines the type of the resulting sustainable long term equilibrium. Therefore it is essential to make assumptions about the auditing probability value p and at first two extreme cases are examined, $\bar{p}$ =1 and $\bar{p} = 0$ respectively.

Assume that the regulator has the ability to control all the firms in the industrial sector simultaneously. This makes the imposition of the legislative abatement level α_L^* certain, under the condition that there are firms that do not comply with the voluntary agreement. This implies that the auditing probability is $\bar{p}$ =1. In this case $C_v(\alpha_V) - C(\alpha_o) < C_L(\alpha_L^*) - C(\alpha_o)$ and $\Omega < 0$, since it is known that the inequality $C(\alpha_o) < C_v(\alpha_V) < C_L(\alpha_L^*)$ holds. As a consequence:

→ If $x_V^* = 1$ then $\frac{d\dot{x}_V}{dx_V} = \Omega < 0$: Stable Equilibrium

→ If $x_V^* = 0$ then $\frac{d\dot{x}_V}{dx_V} = - \Omega > 0$: Unstable Equilibrium

Assume that the regulator makes no inspections in the industry and thus there is no possibility to trace the non-complying firms. Therefore it is certain that the firms will not pay the excessive cost of the legislation mandate. This implies that the auditing probability is equal to zero, meaning that $\bar{p} = 0$. In this case $\Omega = C_v(\alpha_V) - C(\alpha_o) > 0$ since the inequality $C(\alpha_o) < C_v(\alpha_V)$ holds. As a consequence:

→If $x_V^* = 0$ then $\frac{d\dot{x}_V}{dx_V} = - \Omega < 0$: Stable Equilibrium

→ If $x_V^* = 1$ then $\frac{d\dot{x}_V}{dx_V} = \Omega > 0$: Unstable Equilibrium

It is obvious that under a fixed auditing probability p the evolutionary stable equilibrium is always monomorphic. Whether the long-term equilibrium is located at the full compliance $x_V^* = 1$ or the non-compliance $x_V^* = 0$ critical point depends on the existing probability value. It has been already mentioned that there is a critical probability value, defined as $\hat{p}$, that behaves as a bifurcation parameter and affects the final equilibrium. Particularly, each probability value above $\hat{p}$ gives $\Omega < 0$ and makes the full compliance $x_V^* = 1$ steady state stable in the long run (Figure 1a). On the contrast, each probability value underneath $\hat{p}$ gives $\Omega > 0$ and makes the non compliance $x_V^* = 0$ steady state stable in the long run (Figure 1b).

All these could be summarized to the following simple proposition:

Proposition 1: *"Under a fixed auditing probability the sustainable equilibrium in the long run is monomorphic. If* $p \in (\hat{p}, 1]$ *then all the firms comply with the agreement and* $x_V^* = 1$ is the *equilibrium outcome. On the other hand, if* $p \in [0, \hat{p})$ *then none firm complies with the agreement and* $x_V^* = 0$ *is the equilibrium outcome."*

However, in the previous definition of the long-term sustainable equilibrium we did not take in mind the evolution of emission stock over time. Therefore it is essential to introduce an emission dynamic equation that captures the impact of firms' abatement decisions on the evolution of the emission stock in the industrial environment. Particularly, this dynamic equation is defined as:

$$\dot{S}_e = \sum_{i=1}^{n} e_i(\alpha_i) - bS_e \qquad (13)$$

The term $\sum_{i=1}^{n} e_i(\alpha_i)$ denotes the emission loading, the total amount of emissions produced in the industrial sector. On the other hand, the parameter b defines the rate of emission loss per unit stock and therefore the term bS_e denotes the environmental ability to absorb some of this pollution and therefore clean itself.

Furthermore, under the assumption that all the firms are identical the first term can be rewritten and thus the emission dynamic gets the following form:

$$\dot{S}_e = n\{x_V e(\alpha_V) + (1 - x_V)[(1 - \overline{p})e(\alpha_o) + \overline{p}e(\alpha_L^*)]\} - bS_e \qquad (14)$$

The term $nx_V e(\alpha_V)$ reflects the emissions produced by the firms that voluntarily comply with the regulator and implement the abatement level α_V. On the other hand, the second term $n(1 - x_V)[(1 - \overline{p})e(\alpha_o) + \overline{p}e(\alpha_L^*)]$ reflects the emissions produced by the firms that do not comply with the agreement's provisions and implement either the cost minimizing abatement α_o or the mandatory abatement α_L^* that is imposed to them legislatively under a fixed probability $\overline{p}$.

The equations (12) and (14) form a dynamic system, which determines both the equilibrium compliance proportion x_V^* and the equilibrium emission stock level S_e^*. Particularly, the system has the following structure:

$$\dot{x}_V = x_V(x_V - 1)\{C_V(\alpha_V) - C(\alpha_o) - \overline{p}[C_L(\alpha_L^*) - C(\alpha_o)]\}$$
$$\dot{S}_e = n\{x_V e(\alpha_V) + (1 - x_V)[(1 - \overline{p})e(\alpha_o) + \overline{p}e(\alpha_L^*)]\} - bS_e$$

The equilibria of the replicator dynamic have been already found and are set equal to $x_V^* = 1$ and $x_V^* = 0$. If these critical points are substituted into the emission dynamic equation, then the relative emission stock equilibria are determined respectively. After setting $\dot{S}_e = 0$, the following are obtained:

$$\text{For } x_V^* = 1 \rightarrow \dot{S}_e = 0: \; S_e^* = \frac{ne(\alpha_V)}{b}$$

$$\text{For } x_V^* = 0 \rightarrow \dot{S}_e = 0: \; S_e^{**} = \frac{n\{(1-\overline{p})e(\alpha_o) + \overline{p}e(\alpha_L^*)\}}{b}$$

While the replicator dynamic's equilibria correspond to two parallel isoclines $x_V^* = 1$ and $x_V^* = 0$ respectively, the relative emission stock isocline $\dot{S}_e = 0$ is defined as an expression of the proportion x_V and is equivalent to:

$$x_V(S) = \{n[e(\alpha_V) - (1-\overline{p})e(\alpha_o) - \overline{p}e(\alpha_L^*)]\}^{-1}\{bS_e - n[(1-\overline{p})e(\alpha_o) + \overline{p}e(\alpha_L^*)]\} \quad (15)$$

The general form of this isocline is $x_V(S) = \alpha + \beta S$. The constant term[16] α and the slope[17] β are assumed to be positive and negative respectively, since the convex combination of the industrial emissions $(1-\overline{p})e(\alpha_o) + \overline{p}e(\alpha_L^*)$ is considered to be higher than the emissions $e(\alpha_V)$ under the agreement. It has been already assumed that the inequality $\alpha_o < \alpha_L^* < \alpha_V$ holds, thus the inequality $e(\alpha_o) > e(\alpha_L^*) > e(\alpha_V)$ is reasonable due to the inverted relationship between the abatement level α and the emission loading $e(\alpha)$. Moreover, it is assumed that the term α is higher than the unit (α>1), since the opposite assumption makes no sense. Particularly, if $\alpha < 1$ then the sustainable full compliance equilibrium would be connected with a zero emission stock level, which intuitively is completely wrong.

The relative results are presented in the Figure 2a and 2b respectively. Particularly, under the assumption that the auditing probability is higher than the critical probability value $\hat{p}$ then in figure 2a the critical point A is the evolutionary stable equilibrium, while the steady state B is an unstable equilibrium. In this case all the firms cooperate with the regulator and voluntarily implement the proposed abatement level α_V. Therefore the achieved equilibrium emission stock S_e^* is located in low levels, but it is uncertain whether it matches with the environmental target e^*_{target}.

On the other hand, the legislation probability can be lower than the critical value $\hat{p}$. In this case the critical point B is the sustainable equilibrium in the long run, while the critical point A is unstable in figure 2b. As a consequence none firm complies with the offered agreement and implements either the abatement level α_o or the level α_L. Moreover, the achieved equilibrium emission stock S_e^{**} is located in high levels and it might approximate the maximum amount of emissions in the industrial sector.

The main conclusion is that under a fixed probability of a legislation mandate the resulting sustainable equilibrium is always monomorphic. The dynamic system can balance either at the full compliance equilibrium with low emission stock or at the

---

[16] Where $\alpha = -\{n(1-\overline{p})e(\alpha_o) + n\overline{p}e(\alpha_L)\}[n\{(1-\overline{p})e(\alpha_o) + \overline{p}e(\alpha_L)\}]^{-1} > 0$, since $e(\alpha_V) < e(\alpha_L) < e(\alpha_o)$ and $e(\alpha_V) < (1-\overline{p})e(\alpha_o) + \overline{p}e(\alpha_L)$.

[17] Where $\beta = b[ne(\alpha_V) - n\{(1-\overline{p})e(\alpha_o) + \overline{p}e(\alpha_L)\}]^{-1} < 0$.

non-compliance equilibrium with high emission stock. Nevertheless, with the proper design of the offered agreement the regulator can induce all the firms to comply with the agreement. It is obvious that this can be achieved through the announcement of an auditing probability value above the critical value $\widehat{p}$.

Case 2: Compliance dependent auditing probability

Suppose that the probability p depends on the proportion of the firms that comply with the agreement and finally implement the voluntary abatement α_V. It is logical to consider that the probability p decreases as the fraction of complying firms x_V increases. Particularly, if the proportion of signatory firms in the industry is low then it is reasonable to expect that the regulator increases the number of random inspections. As a consequence the localization of non complying firms is more possible and thus the imposition of the legislation mandate becomes more certain. All these could be summarized to this:

$$p = p(x_V) \text{ , with } p'(x_V) < 0 \qquad (15)$$

Therefore, it is interesting to see how this additional assumption affects the equilibrium outcome. The dynamic system is now defined as:

$$\dot{x}_V = x_V(x_V - 1)\{C_V(\alpha_V) - C(\alpha_o) - p(x_V)[C_L(\alpha_L^*) - C(\alpha_o)]\} \qquad (16)$$

$$\dot{S}_e = n\{x_V e(\alpha_V) + (1 - x_V)[(1 - p(x_V))e(\alpha_o) + p(x_V)e(\alpha_L^*)]\} - bS_e \qquad (17)$$

The replicator dynamic's equilibria remain as previously $x_V^* = 1$ and $x_V^* = 0$. Nevertheless there is an additional critical point, defined as $x_V^{\circ\circ\circ} \in (0, 1)$, that sets the expression $\{C_V(\alpha_V) - C(\alpha_o) - p(x_V^{\circ\circ\circ})[C_L(\alpha_L^*) - C(\alpha_o)]\}$ equal to zero and consequently satisfies the equilibrium condition $\dot{x}_V = 0$. In this case the stability derivative, that defines the equilibrium type for each one of these critical points, is equal to:

$$\frac{d\dot{x}_V}{dx_V} = (2x_V - 1)\{C_V(\alpha_V) - C(\alpha_o) - p(x_V)[C_L(\alpha_L^*) - C(\alpha_o)]\}$$

$$- x_V(x_V - 1)\{p'(x_V)[C(\alpha_L^*) - C(\alpha_o)]\}$$

The substitution of these critical points in this expression, give the following:

→ For $x_V^* = 1$ we get $\frac{d\dot{x}_V}{dx_V} = \{C_V(\alpha_V) - C(\alpha_o) - p(1)[C_L(\alpha_L^*) - C(\alpha_o)]\}$

One could easily assume that if all the firms in the industry comply with the agreement and implement the abatement level α_V, then the legislative threat makes no sense. Firms know there is no chance to pay the excessive cost $C(\alpha_L^*) - C(\alpha_o)$, since none non-complying firm will be "traced" by the regulator, no matter the number of inspections he makes. As a consequence the auditing probability is equal to zero, meaning that $p(1) = 0$. Of course this demands that the regulator considers that the signatory firms have no intention to full him, meaning that they might decide not to comply with the agreement's provisions even though they have undersigned it.

Under this simplifying assumption the full compliance equilibrium $x_V^* = 1$ is unstable, since $\frac{d\dot{x}_V}{dx_V} = C(\alpha_V) - C(\alpha_o) > 0$.

This is a reasonable outcome since polluting firms have a financial incentive to deviate from this equilibrium. Particularly, firms know that when the entire industrial sector complies with the regulator then he responds to this positive outcome with a reduced or even zero number of random inspections. Therefore it is really tempting for some firms to leave the agreement and implement the cost minimizing abatement α_o, since it is rather impossible to be caught and finally pay the excessive legislative cost $C(\alpha_L^*) - C(\alpha_o)$.

This conclusion can be summarized to the following proposition:

Proposition 2: *"If the auditing probability is compliance dependent, then announcement of full compliance causes instability."*

→ For $x_V^* = 0$ we get $\dfrac{d\dot{x}_V}{dx_V} = -\{C(\alpha_V) - C(\alpha_o) - p(0)[C(\alpha_L^*) - C(\alpha_o)]\}$

It is logical to assume the legislation becomes more probable as the proportion x_V of signatory firms decreases. Thus in this case the auditing probability $p(0)$ is expected to be sufficiently high due to the condition $p'(x_V) < 0$. However it would be wrong to assume that $p(0) = 1$, even though it would be convenient[18], since the regulator can increase the number of the random inspections but can not monitor all the firms simultaneously. This implies that $0 < p(0) < 1$ and particularly the probability $p(0)$ is high enough to define positively the stability derivative.

Under this assumption the non-compliance equilibrium $x_V^* = 0$ is unstable in the long run, since $\dfrac{d\dot{x}_V}{dx_V} > 0$.

This is a reasonable outcome since firms have a financial incentive to comply with the regulator and voluntarily implement the abatement level α_V. Under the particular circumstances, the non-complying firms know that it is almost certain to be caught and punished legislatively. Therefore, it is preferable for them to comply with the agreement and pay the voluntary excessive cost $C(\alpha_V) - C(\alpha_o)$ rather than to pay the almost certain legislative cost $C(\alpha_L) - C(\alpha_o)$.[19] As a consequence, it is tempting for them to switch their strategy and comply with the regulator's proposal.

→ For $x_V^{\circ\circ\circ} \in (0, 1)$ we get $\dfrac{d\dot{x}_V}{dx_V} = -x_V^{\circ\circ\circ}(x_V^{\circ\circ\circ} - 1)\{p'(x_V^{\circ\circ\circ})[C(\alpha_L^*) - C(\alpha_o)]\} < 0$.[20]

It is noticeable that the stability derivative of the particular steady state is independent of the existing auditing probability value $p(x_V)$. This implies that the critical point $x_V^{\circ\circ\circ}$ is always sustainable in the long run and therefore the dynamic

---

[18] In this case the non-compliance steady state $x_V^* = 0$ is unstable: $\dfrac{d\dot{x}_V}{dx_V} > 0$, since $C(\alpha_V) - C(\alpha_o) < C(\alpha_L^*) - C(\alpha_o)$.

[19] Since $C(\alpha_V) - C(\alpha_o) < C(\alpha_L^*) - C(\alpha_o)$.

[20] Since $p'(x_V) < 0$, $x_V^{\circ\circ\circ} - 1 < 0$ and $C(\alpha_L^*) - C(\alpha_o) > 0$.

system balances in a polymorphic equilibrium, combining both complying and non-complying firms, no matter the existing probability value.

At the compliance proportion $x_V^{\circ\circ\circ}$ corresponds a critical probability value[21] $p(x_V^{\circ\circ\circ})$ that behaves as a bifurcation parameter and affects the stability of the rest steady states $x_V^* = 0$ and $x_V^* = 1$ respectively. It is obvious that any other auditing probability value switches the sign of the expression $\{C(\alpha_V) - C(\alpha_o) - p(x_V)[C(\alpha_L^*) - C(\alpha_o)]\}$ and through it the sign of the stability derivative.

Particularly if the compliance fraction x_V is underneath the critical value $x_V^{\circ\circ\circ}$, then the auditing probability $p(x_V)$ is higher than $p(x_V^{\circ\circ\circ})$. As a consequence $\frac{d\dot{x}_V}{dx_V} > 0$ and the non-compliance equilibrium $x_V^* = 0$ is unstable (Figure 3a). On the other hand if the compliance fraction x_V is above $x_V^{\circ\circ\circ}$, then the probability $p(x_V)$ is underneath the critical value $p(x_V^{\circ\circ\circ})$ and the full compliance equilibrium is unstable since $\frac{d\dot{x}_V}{dx_V} > 0$ (Figure 3b). Both diagrams indicate that the initial distribution of complying firms, therefore and the existing auditing probability value, do not affect the equilibrium outcome and thus the particular dynamic system always leads to a polymorphic stable equilibrium.

Therefore the following proposition holds:

<u>Proposition 3:</u> *"Under compliance x_V dependent auditing probability the evolutionary stable equilibrium is always polymorphic and independent of the existing probability value $p(x_V)$."*

If the replicator's equilibria are substituted into the emission dynamic equation $\dot{S}_e = 0$, then the relative emission stock equilibria are determined respectively. Particularly, we obtain:

For $x_V^* = 1 \rightarrow S_e^* = \frac{ne(\alpha_V)}{b}$

For $x_V^* = 0 \rightarrow S_e^{**} = \frac{n\{(1-p(0))e(\alpha_o) + p(0)e(\alpha_L^*)\}}{b}$

For $x_V^{\circ\circ\circ} \in (0, 1) \rightarrow S_e^{\circ\circ\circ} = \frac{n\{x_V^{\circ\circ\circ} e(\alpha_V) + (1-x_V)[(1-p(x_V^{\circ\circ\circ}))e(\alpha_o) + p(x_V^{\circ\circ\circ})e(\alpha_L^*)]\}}{b}$

The zero compliance auditing probability $p(0)$ is greater than the partial compliance probability $p(x_V^{\circ\circ\circ})$ and consequently the equilibrium emission stock S_e^{**} is higher than the level $S_e^{\circ\circ\circ}$. Moreover, there is no doubt that the full compliance emission stock S_e^* approximates the minimum feasible emission level. Therefore it is

[21] Where $p(x_V^{\circ\circ\circ}) = \frac{C_V(\alpha_V) - C(\alpha_o)}{C_L(\alpha_L^*) - C(\alpha_o)}$.

doubtless that the polymorphic equilibrium is implying a medium size emission stock[22] level, as it can be seen from the relative diagrams.

Finally, it is interesting to define the relationship between the compliance fraction x_V and the legislative abatement level α_L^*. Of course this demands that the regulator can affect the abatement α_L and through it the excessive cost $C(\alpha_L^*)-C(\alpha_o)$ that the legislation mandate implies. After taking the total derivative of the expression $C(\alpha_V)-C(\alpha_o)-p(x_V)\{C(\alpha_L^*)-C(\alpha_o)\}$, we get:

$$\frac{dx_V}{d\alpha_L}=-\frac{p(x_V)C'(\alpha_L^*)}{p'(x_V)C(\alpha_L^*)}>0$$

It is obvious that the higher the legislative abatement α_L^* is, the higher the excessive cost $C(\alpha_L^*)-C(\alpha_o)$ is too. Therefore the proportion of complying firms is expected to increase respectively. This result could have an interesting application to the equilibrium outcome. An increase in the abatement α_L^*, increases the equilibrium compliance proportion $x_V^{\circ\circ\circ}$ and shifts the relative isocline $x_V^{\circ\circ\circ}$ upwards to the parallel isocline $x_V^*=1$. Consequently the closer the abatement α_L^* goes to the abatement α_V, the closer the polymorphic equilibrium point C moves to the full compliance critical point A. So under the appropriate adjustments and conditions the steady states $x_V^*=1$ can become sustainable in the long run.

Case 3: Emission stock dependent auditing probability

Assume that the auditing probability depends on the observed emission stock level S_e. It is reasonable to expect that if the existing emission stock is located in high level, the regulator's logical reaction is to increase the number of random inspections in order to "trace" the firms that do not comply with the agreement and do not abate pollution. Therefore the auditing probability, under which non complying firms are caught and finally forced to implement the legislative abatement level α_L^*, appears increased. All these could be summarized to the following:

$$p=p(S_e),\ \text{with}\ p'(S_e)>0 \qquad (18)$$

Under this assumption the dynamic system is defined as:

$$\dot{x}_V=x_V(x_V-1)\{C_V(\alpha_V)-C(\alpha_o)-p(S_e)[C_L(\alpha_L^*)-C(\alpha_o)]\} \qquad (19)$$

$$\dot{S}_e=n\{x_Ve(\alpha_V)+(1-x_V)[(1-p(S_e))e(\alpha_o)+p(S_e)e(\alpha_L^*)]\}-bS_e \qquad (20)$$

The equilibria of the replicator dynamic have been defined to be $x_V^*=1$ and $x_V^*=0$. Additionally there is a critical emission stock level $\widehat{S}_e$ that satisfies the equilibrium condition $\dot{x}_V=0$. Particularly the probability value[23] $p(\widehat{S}_e)$ that corresponds to this level sets the expression $\Omega=\{C_V(\alpha_V)-C(\alpha_o)-p(S_e)[C_L(\alpha_L^*)-C(\alpha_o)]\}$ equal to zero.

In this case the stability derivative has the following form:

---

[22] Since $S_e^{**}>S_e^{\circ\circ\circ}>S_e^*$.

[23] Where $p(\widehat{S}_e)=\dfrac{C_v(\alpha_V)-C(\alpha_o)}{C_L(\alpha_L^*)-C(\alpha_o)}$.

$$\frac{d\dot{x}_V}{dx_V} = (2x_V - 1)\{C_V(\alpha_V) - C(\alpha_o) - p(S_e)[C_L(\alpha_L^*) - C(\alpha_o)]\}$$

However, the long-term sustainability of these steady state points is uncertain and strongly dependent on the existing auditing probability value. Obviously the emission stock level $\widehat{S}_e$, illustrated by a vertical isocline at the S_e axis, possesses a significant role in the resulting equilibrium outcome since it behaves as a bifurcation parameter. Every other probability values switch the sign of the expression Ω and consequently the sign of the stability derivative. Particularly if the observed emission stock level S_e is located on the right of the isocline $\widehat{S}_e$, implying that $S_e > \widehat{S}_e$, then the relative probability value $p(S_e)$ is higher than the critical value $p(\widehat{S}_e)$ and therefore $\Omega < 0$. On the contrast, if the emission stock level S_e is located on the left of the isocline $\widehat{S}_e$, implying that $S_e < \widehat{S}_e$, then the corresponding probability value $p(S_e)$ is lower than the critical value $p(\widehat{S}_e)$ and therefore $\Omega > 0$.

However, whether the prevailing evolutionary stable equilibrium is located at the critical point $x_V^* = 1$ or $x_V^* = 0$, depends mainly on the relationship between the critical emission stock level $\widehat{S}_e$ and the full compliance emission stock level S_e^* and / or the non-compliance stock level S_e^{**} respectively. Three alternative assumptions can be made about this inequality, either that $\widehat{S}_e < S_e^*$, $S_e^{**} > \widehat{S}_e > S_e^*$ or $\widehat{S}_e > S_e^{**}$.

Therefore the dynamic system may lead to the following outcomes:

→ If $\widehat{S}_e < S_e^*$ then $\frac{d\dot{x}_V}{dx_V} > 0$ for $x_V^* = 0$ and $\frac{d\dot{x}_V}{dx_V} < 0$ for $x_V^* = 1$.

Under this assumption both the full and non-compliance emission stock levels are located on the right of the isocline $\widehat{S}_e$. The expression Ω is negatively defined since the existing auditing probability values exceed the critical probability value $p(\widehat{S}_e)$. In this case non-complying firms know that it is more possible to be caught and punished legislatively. Thus the voluntary excessive cost $C(\alpha_V) - C(\alpha_o)$ appears preferable to the potential higher cost of the legislation mandate. As a consequence all the firms comply with the regulator in the long run and the evolutionary sustainable equilibrium appears to be monomorphic. Particularly, the dynamic system balances at the full compliance critical point A and at a sufficiently low emission stock level, while the non-compliance critical point B is unstable (Figure 4a).

→ If $S_e^{**} > \widehat{S}_e > S_e^*$ then $\frac{d\dot{x}_V}{dx_V} > 0$ for $x_V^* = 0$ and $\frac{d\dot{x}_V}{dx_V} > 0$ for $x_V^* = 1$.

Under the assumption that the critical emission level $\widehat{S}_e$ lies between the full and non-compliance emission stock level, the diagrammatic analysis is enriched by a third steady state point. In this case the full compliance critical point A and the non-compliance critical point B are both unstable in the long run, implying that the evolutionary sustainable equilibrium can not be monomorphic (Figure 4b). On the other hand, the additional critical point C indicates a potential polymorphic equilibrium but the equilibrium type of this steady state can not be directly defined.

Therefore it is essential to define the linearization matrix J around the point C, its trace $tr(J)$, the relative determinant $Det(J)$ and discriminant $\Delta = [tr(J)]^2 - 4[Det(J)]$.

Particularly, the Jacobian matrix J is defined as it follows:

$$J = \begin{bmatrix} 0 & -x_V(x_V - 1)p'(\hat{S}_e)\{C(\alpha^*_L) - C(\alpha_o)\} \\ n[e(\alpha_V) - \{(1 - p(\hat{S}_e))e(\alpha_o) + p(\hat{S}_e)e(\alpha^*_L)\}] & n(1 - x_V)p'(\hat{S}_e)\{e(\alpha^*_L) - e(\alpha_o)\} - b \end{bmatrix}$$

The partial derivatives $\frac{d\dot{S}_e}{dS_e}$ and $\frac{d\dot{S}_e}{dx_V}$ have both negative sign, on the contrary to the partial derivative $\frac{d\dot{x}_V}{dS_e}$ which has positive sign. As a consequence the trace[24] $tr(J)$ is negatively defined, while the determinant[25] $Det(J)$ is positively defined. However, the sign of the discriminant Δ is uncertain and can either be positive, negative or even equal to zero. All these imply that the critical point C can either be a stable focus, a stable proper node or even a stable improper node. Nevertheless, the direction of the arrows in the four isosectors around the critical point C indicates that this steady state is a stable focus. Thus the polymorphic steady state is the evolutionary sustainable equilibrium and the dynamic system spirals inwards towards it.

This is an interesting outcome since this equilibrium, in comparison to the other stable equilibria where the steady state is a node, exhibits a circular motion converging to the critical point C. Therefore it worth's understanding the mechanism that leads to this steady state. Assume a starting point in the isosector I, where the auditing probability $p(S_e)$ is lower than the critical value $p(\hat{S}_e)$. Under these circumstances firms are tempted to refuse the agreement and thus the compliance proportion declines, while the total amount of emission stock increases. This behavior continues until the bottom of the cycle since afterwards the auditing probability has increased enough, above the critical value $p(\hat{S}_e)$, to induce non-complying firms to fulfill the agreement's provisions.

Nevertheless, it should not be surprising that in this isosector (II) the observed emission stock levels appear increased since this indicates a lag in the functioning of the voluntarily installed abatement level α_V. Thus when the implemented abatement starts operating the emission stock level starts declining, while the fraction x_V keeps increasing. This behavior continues until the top of the cycle since afterwards the auditing probability declines again, underneath the critical value $p(\hat{S}_e)$, offering the complying firms an incentive not to fulfill the agreement's provisions ex-post. The proportion of complying firms declines and after a point the observed emissions appears increased again. This spiraling motion continues until the system has finally reached the critical point C, where it balances at a medium emission stock level.

$\rightarrow$ If $S_e^{**} < \hat{S}_e$ then $\frac{d\dot{x}_V}{dx_V} < 0$ for $x_V^* = 0$ and $\frac{d\dot{x}_V}{dx_V} > 0$ for $x_V^* = 1$.

---

[24] Where the trace around the point C is equal to $tr(J) = \frac{d\dot{x}_V}{dx_V} + \frac{d\dot{S}_e}{dS_e} = 0 + \frac{d\dot{S}_e}{dS_e} < 0$.

[25] Where the determinant around the point C is $Det(J) = \frac{d\dot{x}_V}{dx_V}\frac{d\dot{S}_e}{dS_e} - \frac{d\dot{x}_V}{dS_e}\frac{d\dot{S}_e}{dx_V} = \frac{d\dot{x}_V}{dS_e}\frac{d\dot{S}_e}{dx_V} > 0$.

In this case both the full and non-compliance emission stock levels are located on the left of the isocline $\widehat{S}_e$. The expression Ω is positively defined since the existing auditing probability values exceed the critical probability value $p(\widehat{S}_e)$. This indicates that even though the observed emission stock is located in high levels, the auditing probability is not high enough to induce the firms to comply with the regulator. Thus firms decide to take the risk and not to fulfill the agreement's provisions, leading to a monomorphic equilibrium outcome. As a consequence none firm complies with regulator in the long run and the dynamic system balances at the non-compliance critical point B and at a sufficiently high equilibrium emission stock level, while the full compliance critical point A is unstable (Figure 4c).

All the above can be summarized to the following proposition:

Proposition 4: *"Under an emission stock S_e dependent auditing probability the sustainable long-term equilibrium can either be polymorphic or monomorphic. If $\widehat{S}_e < S_e^*$, then all the firms comply with the agreement and $x_V^* = 1$ is the equilibrium outcome. If $S_e^{**} > \widehat{S}_e > S_e^*$, then there is partial compliance to the agreement and $x_V^* = x_{3V}$ is the equilibrium outcome. If $S_e^{**} < \widehat{S}_e$, then none firm complies with the agreement and $x_V^* = 0$ is the equilibrium outcome."*

In this point it is interesting to define the relationship that connects the emission stock level S_e and the legislative abatement level α_L^*. Thus by taking the total derivative of the expression $\{C_V(\alpha_V) - C(\alpha_o) - p(S_e)[C_L(\alpha_L^*) - C(\alpha_o)]\}$ we obtain:

$$\frac{dS_e}{d\alpha_L} = -\frac{p(S_e)C'(\alpha_L^*)}{p'(S_e)\{C(\alpha_L^*) - C(\alpha_o)\}} < 0$$

It has been already mentioned that the higher the legislative abatement α_L is, the higher the excessive cost $C(\alpha_L^*) - C(\alpha_o)$ is respectively. Therefore under the threat of a higher abatement level α_L^*, firms know that if they are caught not complying with the agreement then they have to pay a relatively higher legislative cost. Thus firms have an incentive to comply with the regulator and control their emission production. As a consequence the critical emission stock level $\widehat{S}_e$ declines and the relative vertical isocline moves closer to the full compliance emission stock level S_e^*. Moreover the polymorphic equilibrium point C moves closer to the monomorphic steady state point A, implying that with the proper design of the agreement the regulator can induce the majority or even the entity of firms to comply with the agreement.

Case 4: Auditing probability jointly dependent on the emission stock and compliance fraction.

Assume that the auditing probability depends jointly on the observed emission stock level S_e and the proportion of complying firms x_V. In this case the regulator takes simultaneously in mind the existing values of these two global variables, in order to define the final number of random inspections. It has been already mentioned that the probability p decreases as the compliance fraction x_V increases, while it appears increased when the emission stock is located in high levels. Thus it holds:

$$p = p(x_V, S_e)\text{, with } \frac{dp(x_V, S_e)}{dx_V} < 0 \text{ and } \frac{dp(x_V, S_e)}{dS_e} > 0 \qquad (21)$$

Under this complicated assumption the dynamic system's structure is reformed:

$$\dot{x}_V = x_V(x_V - 1)\{C_V(\alpha_V) - C(\alpha_o) - p(x_V, S_e)[C_L(\alpha_L^*) - C(\alpha_o)]\} \qquad (22)$$

$$\dot{S}_e = n\{x_V e(\alpha_V) + (1 - x_V)[(1 - p(x_V, S_e))e(\alpha_o) + p(x_V, S_e)e(\alpha_L)]\} - bS_e \qquad (23)$$

The steady state points that satisfy the replicator dynamic's equilibrium condition $\dot{x}_V = 0$ have been already defined as $x_V^* = 1$ and $x_V^* = 0$ respectively. Nevertheless there is an additional critical point, defined as $x_{3V}^* \in (0, 1)$, that makes zero the expression $\Omega = [C(\alpha_v) - C(\alpha_o) - p(x_V, S_e)\{C(\alpha_L) - C(\alpha_o)\}]$ and therefore satisfies the required equilibrium condition.

The isocline that corresponds to this equilibrium point is defined as a function of the observed emission stock level S_e and has the following form:

$$x_V(S_e): C(\alpha_v) - C(\alpha_o) - p(x_V, S_e)\{C(\alpha_L) - \mathrm{C}(\alpha_o)\} = 0$$

All the (x_V, S_e) combinations lying along this isocline satisfy the equality $\Omega = 0$. Furthermore, the corresponding probabilities $p(x_V, S_e)$ behave as bifurcation parameters, since every other (x_V, S_e) combination switches the sign of the expression Ω and finally affects the equilibrium outcome, as it is seen below. Particularly, each combination located on the left of the isocline gives $\Omega > 0$, while combinations located on the right give $\Omega < 0$.

Moreover, the stability derivative is defined as:

$$\frac{d\dot{x}_V}{dx_V} = (2x_V - 1)\{C_V(\alpha_V) - C(\alpha_o) - p(x_V, S_e)[C_L(\alpha_L^*) - C(\alpha_o)]\}$$
$$- x_V(x_V - 1)\{p'(x_V, S_e)[C(\alpha_L) - C(\alpha_o)]\}$$

While the replicator's dynamic equilibria $x_V^* = 1$ and $x_V^* = 0$ correspond to two parallel isoclines, the isocline $x_V(S_e)$ of the additional critical point x_{3V}^* has positive slope. Particularly, this slope is the ratio of the auditing probability's partial derivatives with respect to the global variables S_e and x_V respectively, and is equal to:

$$\frac{dx_V}{dS_e} = -\frac{\partial p(x_V, S_e)/\partial S_e}{\partial p(x_V, S_e)/\partial x_V} > 0$$

In this case the partial derivatives reflect the firms' beliefs about the variability of the auditing probability's value due to changes realized on the global variables' values. For example, if polluting firms give high significance in increases realized on the observed emission stock level, then both the probability value $p(x_V, S_e)$ and the relative partial derivative are expected to be high.[26] It is obvious that the relative importance that firms give on the global variables' changes influences the existing auditing probability $p(x_V, S_e)$ value, affecting the isocline's $x_V(S_e)$ slope and possibly the potential equilibrium outcome.

[26] The same applies for reductions realized on the compliance proportion.

Suppose that there is an isocline $x_V(S_e)$, which passes through the full compliance critical point A and its slope is defined as $\left(\frac{dx_V}{dS_e}\right)_1$. This isocline is introduced in the analysis in order to distinguish between the potential long-term equilibria that the dynamic system may lead to. Particularly, the following can be identified:

→ Assume that the firms perceive that the auditing probability's value is more "sensitive" on compliance proportion changes, or alternatively that it is less "sensitive" on emission stock changes. In this case the isocline $x_V(S_e)$ is flatter, since the relative slope is less than $\left(\frac{dx_V}{dS_e}\right)_1$, and cuts the emission stock dynamic isocline $\dot{S}_e = 0$ at the critical point C. As it can be seen in the figure 8a this equilibrium point is located on the right of the full compliance steady state point A.

However, the diagram indicates that the full and non-compliance critical points can not be sustainable in the long-run. Particularly, on the left of the isocline the auditing probability is lower than its critical value and $\Omega > 0$, giving $\frac{d\dot{x}_V}{dx_V} > 0$ for $x_V^* = 1$. Firms know that the excessive legislative cost is less probable and thus firms have a financial incentive to refuse the agreement. On the other hand, on the right of the isocline the auditing probability is higher than the critical value and $\Omega < 0$, giving $\frac{d\dot{x}_V}{dx_V} > 0$ for $x_V^* = 0$. The excessive legislative cost becomes more probable for non-complying firms, which are tempted to comply with the agreement. Under these circumstances the polymorphic critical point C is the evolutionary stable equilibrium, implying an emission level of medium size and a partial compliance to the agreement.

It is noticeable that if the firms do not believe that changes in the observed emission stock level can affect the auditing probability value, then the partial derivative $\frac{\partial p(x_V, S_e)}{\partial S_e}$ is equal to zero. Thus the auditing probability depends only on the proportion of complying firms and the isocline $x_V(S_e)$ is parallel to the horizontal axis, reminding us the already examined case 2. Therefore someone could easily imply that the case of the compliance dependent auditing probability $p(x_V)$ is a special sub case of the combined probability $p(x_V, S_e)$.

→ Assume that the firms perceive that the auditing probability's value is more "sensitive" on emission stock changes, or alternatively that it is less "sensitive" on compliance proportion changes. Under these circumstances the isocline $x_V(S_e)$ is more vertical, since the relative slope is higher than $\left(\frac{dx_V}{dS_e}\right)_1$, and cuts the emission stock dynamic isocline $\dot{S}_e = 0$ at the critical point C. As it can be seen in the figure 5b this equilibrium point is located on the left of the full compliance steady state point A.

However, this steady state is located in an unfeasible area of (x_V, S_e) combinations since it lies above the $x_V^* = 1$ isocline. Consequently the critical point C does not exist as an option and the dynamic system balances compulsory at one of the two monomorphic steady states. On the right of the isocline $x_V(S_e)$ the corresponding probability values $p(x_V, S_e)$ are higher than the critical values, giving $\Omega < 0$. In this case the stability derivative $\frac{d\dot{x}_V}{dx_V}$ is positively defined for $x_V^* = 0$ and negatively defined for $x_V^* = 1$. This indicates that in the long run it is profitable for firms to comply with the agreement and therefore the full compliance point A is the evolutionary stable equilibrium, implying a low emission stock equilibrium level.

It is noticeable that if the firms do not expect that the auditing probability value is affected by changes in the compliance fraction, then the partial derivative $\frac{\partial p(x_V, S_e)}{\partial x_V}$ is equal to zero. Therefore the auditing probability depends only on the observed emission stock and the isocline $x_V(S_e)$ is vertical to the horizontal axis, particularly it matches with the x_V axis. This reminds the already examined case 3 and can lead to the conclusion that the case of emission stock dependent auditing probability is a special sub case of the combined probability $p(x_V, S_e)$ respectively.

All the above can be summarized in the following concluding remark. It is obvious that the flatter the isocline $x_V(S_e)$ is, the more probable is that the evolutionary stable equilibrium is polymorphic. Thus in the long run only partial compliance can be achieved and the relative equilibrium emission stock is of medium size. On the other hand the more vertical the isocline $x_V(S_e)$ is, the more probable is that the long-term sustainable equilibrium is monomorphic. Particularly in the long run all the firms comply with the agreement and the relative equilibrium emission stock is at the lower feasible level.

Nevertheless, the equilibrium outcome can be further affected through the legislative abatement level α_L^*, since it determines the position of the isocline $x_V(S_e)$. It has been already mentioned that the higher the abatement level α_L is, the more firms tend to comply with the agreement and control their emission production. Consequently the regulator can shift the isocline $x_V(S_e)$ upwards, bringing the polymorphic equilibrium point C closer to the monomorphic steady state point A, through the announcement of a sufficiently higher legislative abatement level. Therefore, it is logical to expect that under the proper design the dynamic system can eventually balance at the full compliance critical point, with lower realized emissions.

All these could be summarized to the following simple proposition:

Proposition 5: *"Under an auditing probability with joint dependence on compliance proportion x_V and emission stock S_e the evolutionary sustainable equilibrium can alternatively be polymorphic or monomorphic, depending mainly on the slope and position of the isocline $x_V(S_e)$. The flatter the isocline $x_V(S_e)$ is, the more probable is that the long-term stable equilibrium is of partial compliance. The more vertical the isocline $x_V(S_e)$ is, the more probable is that in the long-term sustainable equilibrium is of full compliance."*

VI. The Evolutionary Equilibrium under a Non-Linear Emission Stock Dynamic Equation

In the previous section the analysis for the derivation of the evolutionary stable equilibrium, was based on the assumption that the evolution of the emission stock over time is described by a linear dynamic equation. Nevertheless, this is not always valid since ecological systems often display nonconvexities and hysteresis in their behavior. In many cases has been noticed that when the emission stock becomes too high, *"it sets off an internal positive feedback mechanism which impairs the ecosystem's ability to absorb and biodegrade loadings"* as Brock & Starrett (1999) underline in their work.

Characteristic examples of such behaviour are shallow lakes. [27] Lakes are so-called "waste sinks" since they are the final recipient of agricultural fertilizers[28], washed into them due to erosion, and waste water, due to human activities. It is evident that for low emission stock, any additions tend to be accumulated in the lake bed and the marginal returns to the environment are relatively low. However, higher emission stocks stimulate the excessive growth of aquatic vegetation[29], causing eutrophication. Dense algal blooms form near the surface, preventing the sun light to reach algae at the lake bottom. The submerged vegetation disappears, forming dense organic ooze that consumes the oxygen dissolved in the surrounding water. As a result the decay of dead algae causes toxic blooms, species disappearance, episodes of anoxia that recycle phosphorus from lake sediments and loss of freshwater ecosystem services[30].

Therefore there is no doubt that the emission stock dynamic equation should be extended by an additional term, which captures the positive feedback processes that operate inside a typical industrial environment when observed emission stock becomes too high. Under these circumstances the emission dynamic equation is considered to have the following general non-linear form:

$$\dot{S}_e = a - bS_e + f(S_e) \qquad (24)$$

The term $f(S_e)$ denotes the internal feedback input of emission stock due to the environmental "ability" to produce emissions under certain circumstances. On the other hand, the term a denotes the external input of emission stock due to industrial activity and has been already defined as $n\{x_V e(\alpha_V) + (1-x_V)[(1-p)e(\alpha_o) + pe(\alpha^*_L)]\}$. It is obvious that the sum of these two terms reflects the total amount of emissions released in the industrial environment.

Nevertheless the term $f(S_e)$ can be further specified and be set equal to the ratio $f(S_e) = g\dfrac{S_e^2}{1+S_e^2}$, as Mäler & all suggest in their paper. Thus the emission stock dynamic equation can be rewritten as:

$$\dot{S}_e = n\{x_V e(\alpha_V) + (1-x_V)[(1-p)e(\alpha_o) + pe(\alpha^*_L)]\} - bS_e + g\frac{S_e^2}{1+S_e^2} \qquad (25)$$

The relative isocline $\dot{S}_e = 0$, as an expression of the fraction x_V, is defined as:

---

[27] For better understanding see the relative figure at the Appendix, page 40.

[28] Especially of the nutrient phosphorus.

[29] Known as phytoplankton.

[30] As freshwater ecosystem services can be identified the drinking water, water for irrigation and industrial use, fisheries and recreation.

$$x_V = -\alpha + \beta S_e - A^{-1} g \frac{S_e^2}{1+S_e^2}$$

, with $\alpha > 0$, $\beta < 0$, $A < 0$ and g a positive natural parameter.[31] Both linear and non-linear emission dynamic equations have the same constant term α and therefore they start from the same point at the x_V axis. Nevertheless, the feedback term is convex-concave and increasing in the emission stock level. As a consequence the emission stock dynamic equation (25) is respectively convex-concave and is illustrated as a "S-shaped" curve, that is characterized by discontinuities in the equilibrium steady states over time, as it is seen in the relative figures 6 and 7 respectively. However, the particular diagrammatic illustration should not be taken for granted since this isocline resulted under particular parameter values[32].

Therefore in this case the dynamic system is restructured as follows:

$$\dot{x}_V = x_V (x_V - 1)\{C_V(\alpha_V) - C(\alpha_o) - p[C_L(\alpha_L^*) - C(\alpha_o)]\}$$

$$\dot{S}_e = n\{x_V e(\alpha_V) + (1 - x_V)[(1-p)e(\alpha_o) + pe(\alpha_L^*)]\} - bS_e + g\frac{S_e^2}{1+S_e^2}$$

The applied methodology for the definition of the replicator's dynamic and emission stock long-term equilibria remains as previously the same and the results are still dependent on the feature of the auditing probability. Consequently the following sub-cases can be identified about the resulting equilibrium:

→ Assume that the auditing probability is fixed and known to the polluting firms. It has been already mentioned that in this case the evolutionary sustainable equilibrium is monomorphic. Nevertheless, whether or not there is full compliance with the agreement it depends on the relationship between the existing probability $\bar{p}$ and the critical value $\hat{p}$.

Particularly if the auditing probability is lower than the critical value, implying that $\bar{p} < \hat{p}$, then none firm complies with the agreement in the long run and implements either the cost minimizing abatement α_o or the legislatively imposed abatement α_L^*. In the figure 6a the evolutionary sustainable steady state is located in the point F, where the corresponding equilibrium emission stock is equal to the level S_{1e}^{**}. It is obvious from the diagram that under the linear emission dynamic equation (14) the relative non-compliance critical point B is preferable since it is connected with a lower emission stock level S_e^{**}.

On the other hand if the auditing probability is higher than the critical value, implying that $\bar{p} > \hat{p}$, then all the firms comply with the regulator and voluntary abate pollution. As the diagram 6a indicates there are multiple full compliance steady states, implying different equilibrium emission stock levels. The steady states C, D & E lead to higher equilibrium emission stock levels and inferior environmental conditions, compared to the relative critical point A resulting under the linear dynamic equation. Nevertheless only the equilibria C and E are stable in the long-run, while the steady state point D is unstable. Compared to the relative critical point A, the critical point E

[31] Where $A = n[e(\alpha_V) - \{(1-p)e(\alpha_o) + pe(\alpha_L^*)\}] < 0$, since $e(\alpha_V) < (1-p)e(\alpha_o) + pe(\alpha_L^*)$.

[32] This curve was designed in the MATHEMATICA 4 WOLFRAM RESEARCH program and resulted for the parameter values $\alpha = 1.1$, $b = 0.7$ and $g = 1.2$.

is bad full compliance equilibrium since the system balances to the sufficiently high emission stock level S_{3e}^*. However, the most important is that the steady state E is an irreversible long-term equilibrium.

It is known that the area above the isocline $x_V^* = 1$ is unfeasible. Particularly, if the system balances in the critical point E it can not converge to the steady state C, since this can be achieved only with compliance proportions higher than the unit. Thus once the emission stock exceeds a certain critical level (S_{2e}^*), there is no policy that can ever lead the system again to lower emission levels (S_{1e}^*). Such ecosystems are so-called vulnerables, since they may change substantially after a shock and remain in that "dirty" state, without returning to the "clean" state that existed prior the shock. Literately the dynamic system is "trapped" in this bad equilibrium and it is impossible to restore the system in an environmental friendlier state, even if the external emission loading is reduced to zero.

All these could be summarized to the following simple proposition:

Proposition 6: "*Under a fixed auditing probability and a non-linear emission stock dynamic equation it is possible that the dynamic system is trapped in a bad irreversible steady state. Moreover, the evolutionary sustainable monomorphic equilibrium, either of full or non-compliance, is environmentally inferior since the equilibrium emission stock levels are higher than the relative equilibria under the linear dynamic equation.*"

→ Assume that the auditing probability depends on the proportion of complying firms. It has been already mentioned that under this assumption the long-term stable equilibrium is polymorphic, implying partial compliance with the regulator. In the figure 8b this steady state is located in the point H, where the corresponding equilibrium emission stock is defined as $S_{1e}^{\circ\circ\circ}$. It is undoubtful that this critical point is environmentally inferior to the relative critical point G, under the linear dynamic equation. As the diagram indicates for the same equilibrium compliance fraction $x_V^{\circ\circ\circ}$ the steady state H implies higher equilibrium emission stock than the relative "linear" level $S_e^{\circ\circ\circ}$. Thus the steady state point G under the linear equation is preferable than the relative long-term equilibrium under the non-linear equation.

It has been already mentioned that an increase in the legislative abatement shifts the isocline $x_V^{\circ\circ\circ}$ upwards, bringing it closer to the full compliance isocline $x_V^* = 1$. Moreover the polymorphic critical point moves closer to the full compliance steady state. Nevertheless as the abatement level α_L^* goes closer to the voluntary abatement level α_V, the isocline $x_V^{\circ\circ\circ}$ cuts the non-linear emission stock isocline $\dot{S}_e = 0$ in more than one point, leading to multiple polymorphic steady states. Under this condition the dynamic system may balance either in an environmentally beneficial critical point, compared to the initial steady state[33] H, or in a bad and irreversible critical point, such as the steady state E in the previous diagram.

In this case the following proposition holds:

Proposition 7: "*Under compliance dependent auditing probability and a non-linear emission stock dynamic equation, the higher the legislative abatement level is the*

[33] And not compared to the "linear" steady state point G.

more probable a bad irreversible polymorphic equilibrium is. Moreover, the evolutionary sustainable polymorphic equilibrium leads to higher equilibrium emission stock level than the linear emission stock dynamic equation does."

All the above can be summarized to the following simple concluding remark. Ecosystems that display internal feedback loading mechanisms lead always the dynamic systems to environmental inferior sustainable long-term equilibria and in many cases this is an irreversible situation. Finally the sub-cases, under which the auditing probability is emission stock dependent or simultaneously dependent on the emission stock and compliance fraction, are not examined in this thesis due to the growing complexity that they imply.

VII. Conclusions

The purpose of the present master thesis was to examine the evolution of compliance to the environmental regulation, jointly with the evolution of realized emission stock in an industrial sector. Its main intention was to determine the equilibrium fraction of complying firms x_V^*, as well as the corresponding equilibrium emission stock level S_e^*, resulting both in the long-term under different assumptions about the behavior of a certain parameter of the problem. An evolutionary process was utilized that combined both the replicator dynamic equation $\dot{x}_V$ and the emission stock dynamic equation $\dot{S}_e$. The general conclusion of the above analysis is that the value and structure of the auditing probability- the possibility that during the random inspections firms are caught non to comply with the agreed environmental target- appeared to be of crucial significance for the resulting equilibrium outcome and can either lead to a monomorphic or polymorphic steady state.

It is assumed that the auditing probability could alternatively be fixed or dependent on global variables, such as the total emission stock and the existing compliance proportion. This assumption appears to affect the firms' final decision about their strategic behavior in the industrial sector and therefore the observed emission stock level. Particularly, polluting firms has to choose between two alternative strategies: either to comply with the regulator and voluntarily implement the proposed abatement level α_V, or to adopt ex-ante or ex-post the non-complying behavior and implement the cost minimizing abatement level α_o or the probabilistic abatement level α_L^* imposed to them legislatively.

The above analysis indicates that in the long run the dynamic system balances either in a monomorphic steady state or alternatively in a polymorphic steady state. It is defined that if the long-term equilibrium is monomorphic then all the firms adopt a homogenous strategic behavior and there is either full compliance or non-compliance to the agreement's provisions. On the other hand if the long-term equilibrium is polymorphic then heterogeneity is observed in the industrial sector relatively to the firms' strategic behavior, implying that only a proportion of firms accept to fulfill the agreement's provisions and abate pollution while the remaining proportion denies complying with the regulator.

Particularly it is shown that when the auditing probability is fixed then the evolutionary sustainable critical point is always monomorphic. The same outcome is achieved under certain initial condition when the auditing probability was dependent on specific global variables. On the other hand, the evolutionary sustainable critical point is always polymorphic when the auditing probability depends either on the compliance proportion x_V, the observed emission stock S_e or jointly on both of these variables. It is also shown that when the probability p is emission stock dependent and if a specific inequality holds then the resulting long-term critical point is a stable focus, while in all the rest cases the relative critical points are a stable node.

If in the long run the equilibrium outcome implies full compliance to the regulation then the dynamic system balances in a high environmental quality level or alternatively in a low emission stock level. A medium environmental quality is achieved if the long-term steady state implies polymorphic strategic behavior. A high enough equilibrium emission stock level and thus low environmental quality, is also possible if the entity of firms adopts the non-complying behavior in the long run. Moreover, the analysis indicates that when the emission stock dynamic equation is extended by an internal feedback mechanism then it is possible that the dynamic system is trapped in a bad equilibrium and can not be restored in an environmental friendlier state. Under this particular assumption the dynamic system leads always to environmental inferior sustainable long-term equilibria, compared to a dynamic system that contains a linear emission stock dynamic equation.

The general conclusion of the present master thesis is that the regulator can lead the equilibrium outcome closer or even on the full-compliance steady state point, through the appropriate design of the voluntary agreement. Particularly, the closer the legislatively imposed abatement level α_L^* goes to the voluntarily implemented abatement level α_V, the closer the polymorphic equilibrium critical point moves to the full compliance critical point. As a consequence the dynamic system balances in a lower emission stock equilibrium level, improving the observed environmental quality in the industrial sector. Finally the full compliance to the environmental regulation can be achieved with certainty if the regulator commits to a fixed auditing probability that is set above the relative critical value.

The increasing demand for adequate internalization of environmental externalities in a long-term base and the relatively little research work that has been done on the evolutionary sustainability of voluntary environmental agreements, suggest that there is enough room for further research and new results. The utilized evolutionary framework can be also applied to address issues such as the evolution of social norms and regulatory frameworks in non-point source pollution problems, the social welfare optimization problem that characterizes regulation and the category of international environmental agreements. Moreover, it can be applied to compare the voluntary versus mandatory instruments in a welfare base. Finally the exploration of the implication of the evolutionary methodology for the regulation of specific issues such as agricultural non-point source pollution, water management and tax evasion appears really tempting and may offer interesting information for efficient environmental policy making.

VIII. References

1. Brock W. and Starrett D., 1999, "NonConvexities in Ecological Management Problems", Resource and Energy Economics, forthcoming
2. Dawson N.L. and Segerson K., 1999, "Participation in industry-wide voluntary approaches: short-run vs. long-run equilibrium", in J. List and A. de Zeeuw (Eds), Recent Advances in Environmental Economics, 142-157, E. Elgar.
3. Gintis H., 2000, "Evolutionary Dynamics", in Game Theory Evolution, Princeton University Press, pages 188-219.
4. Khanna M. and Damon L. A., 1999, "EPA's Voluntary 33/50 Program: Impact on Toxic Releases and Economic Performance of Firms", Journal of Environmental Economics and Management, Vol. 37, pages 1-25.
5. Ludwig D., Carpenter S. and Brock W., 2002, "Optimal Phosphorus loading for a Potentially Eutrophic Lake", Working Paper, University of Wisconsin, SSRI, 2002-9.
6. Mäler K., Xepapadeas A. and Zeeuw A., "The Economics of Shallow Lakes", Resource and Energy Economics, forthcoming
7. Pesaro G., 2001, "Environmental Voluntary Agreements: A New Model of Co-operation between Public and Economic Actors", Economics Energy Environment, Fondazione Eni Enrico Mattei, pages 1-32.
8. Owen O., Chiras D. and Reganold J., 1998, "Fisheries Conservation", in Natural Resources Conservation, Prentice Hall (ed).
9. Šauer p., Andrews R., Cudlínová E., Dvořák A., Fiala P., Holcová P., Kovář J., Lisa A., Livingston M., Tošovská E., 2001, "Voluntary Agreements in Environmental Policy", VYSOKÁ ŠKOLA EKONOMICA V PRAZE, pages 9-41.
10. Segerson K. and Miceli T., 1998, "Voluntary Environmental Agreements: Good or Bad News for Environmental Protection?", Journal of Environmental Economics and Management, vol 36, pages 109-130.
11. Segerson K., (1998), "Voluntary vs. Mandatory Approaches to Nonpoint Pollution Control: Complements or Substitutes?", Economics Energy Environment , Fondazione Eni Enrico Mattei, 1-37.
12. Xepapadeas A., 2003, "Regulation and Evolution of Harvesting Rules and Compliance in Common Pool Resources", Fundación Centro de Estudios Andaluces (centrA), Documento de trabajo E2003/39.
13. Xepapadeas A., 1998, "Informational Constraints and Nonpoint Source Pollution", in Advanced Principles in Environmental Policy, Edward Elgar (ed), pages 136-169.

IX. Appendix

(I) Voluntary agreements characteristics

Under the UN Framework Convention on Climate Change the IEA Member countries have committed them selves to limit the atmospheric concentration of greenhouse gases. This objective has to be reconciled with the overall objectives of promoting sustainable economic growth, enhancing energy security and ensuring environmental protection in all areas. It is noticeable that the instrument of voluntary environmental agreements account for the 1/10 of measures utilized by countries in order to reach the determined targets.

The Table 1 presents a detailed summary of existing and planned voluntary programs in IEA countries. The countries' programs are listed according to broad sector categories: electricity production including transformation and distribution, industry and processes (primarily fossil fuel uses), residential, commercial and institutional sectors (fossil fuel uses for heating, electricity use for appliances and equipment) and the transport sector. Are listed also countries' programs which have detailed and comprehensive multisectoral monitoring and reporting mechanisms.

Source: International Energy Agency, Voluntary Actions for Energy-Related CO_2 Abatement, Policy and Environment Policy Analysis Series.

Table 1:

Voluntary Approaches in Member Countries to Mitigating Energy-Related Greenhouse Gas Emissions

Country	Electricity Production, Transformation, and Distribution	Industry and Processes (mainly fossil fuel)	Residential Commercial Institutional: Buildings and Homes (fossil fuel uses)	Residential Commercial Institutional: Electric Appliances and Equipment	Transport	Multisectoral Reporting
Australia	Electricity/gas industry: micro-economic reforms to promote more efficient use of resources and the development of the energy services sector	Co-operative agreements with industry for GHG abatement including emissions inventories, action plans, monitoring and reporting	Building codes (agreements) and labelling of gas fired water heating systems		National average fuel consumption targets to the year 2000	National information service on response measures
Austria	Agreements on use of windpower, photovoltaic, biomass, and cogeneration for electricity production	Energy audits for industrial energy consumers				
Belgium	Electricity production: use of gas/steam turbines; promotion of cogeneration (agreements)	(Energy conservation agreements with industry groups; energy audits and energy management support)		(Energy-efficien standards for electrical appliances)		
Canada	Memoranda of Understanding with Industry Associations	Climate Change Voluntary Challenge and Registry (VCR) for all sectors; participants prepare publicly available action plans at company level. Sector wide energy efficiency targets under CIPEC	Energy efficiency in new homes, buildings and corporations	Labelling of household electrical appliances	Fuel efficiency targets for cars and light duty trucks	VCR infobase publicly assessable includes commitments and plans in their entirety
Denmark	Electric utilities: use of wind power; CHP production from biomass; (promotion of gas district heating)	(Energy savings for offshore oil and gas producers, refineries); agreements with greenhouse operators to support energy efficiency measures	(Energy management in public buildings)	(Replacing inefficient appliances)		
Finland	Increasing use of CHP; promotion of renewable energy	Branch agreements for heat saving targets for process industries and SMEs; energy audits	Heat saving targets for public buildings	Electricity saving targets in public buildings; energy labelling for household equipment	Fuel saving targets for public sector operations	
France	Promotion of renewable energy, wind and hydro power; alternative energy use in rural areas	(Possible agreements on energy savings for energy intensive industries)	Use of wood energy, energy audits in public buildings; home energy labelling	Promotion of energy-efficient electric appliances and lighting	Agreement to promote electric and natural gas vehicles	
Germany	CO2 reduction goals for four sectors: electric utilities, gas and water supply, companies, and municipal industrial energy producers	Corporate CO2 or energy reduction goals with specific targets for 15 industry sectors	Labelling scheme for high performance buildings and solar homes; insulation values for existing buildings; reduction goals of fossil fuel use for heating purposes	[Energy-efficien targets for appliances]; eco-labelling of equipment	25% reduction in fuel consumption of new cars from 1990 to 2005	Common reporting framework for industry sectors
Greece		Investment commitment for energy saving in industry groups; energy audits				
Ireland	Increased use of renewables and biomass for energy production	Self-audits and statement of companies' energy accounts	Home energy rating incorporated into building regulations	Labelling for refrigeration appliances and washing machines		
Italy		(Possible agreements on energy efficiency for processes and alternative fuel use)				

( ): planned or being proposed; [ ]: phased-out.

Table 1 (cont.):

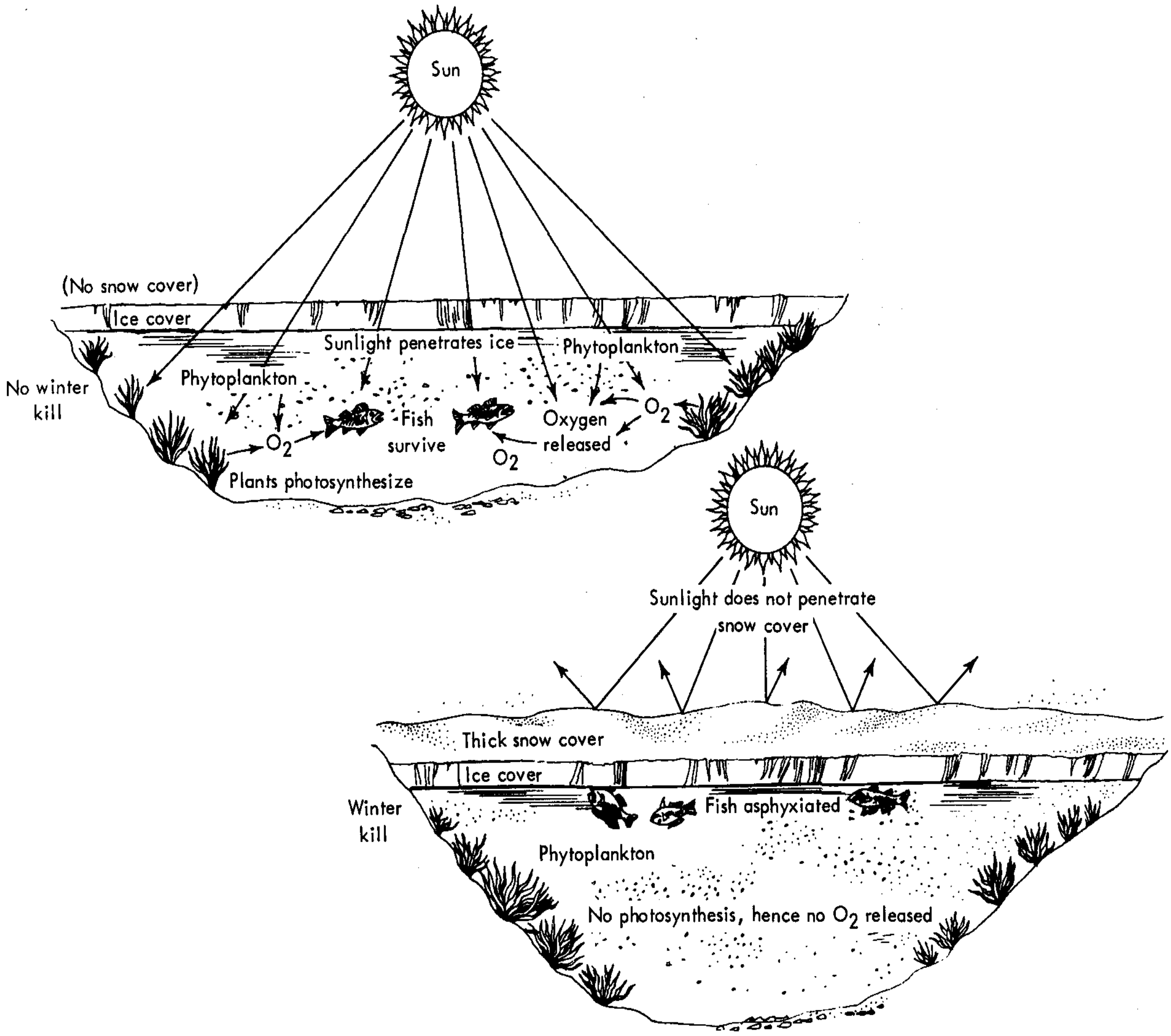
Voluntary Approaches in Member Countries to Mitigating Energy-Related Greenhouse Gas Emissions

Country	Electricity Production, Transformation, and Distribution	Industry and Processes (mainly fossil fuel)	Residential/Commercial/Institutional		Transport	Multisectoral Reporting
			Buildings and Homes (fossil fuel uses)	Electric Appliances and Equipment		
Japan	Energy-efficiency improvements; NOx reduction; use of CHP in power plants and renewables	Corporate energy conservation targets and GHG emission reductions for industry sectors			8.5% fuel-efficiency target for the year 2000 for passenger cars and light duty vehicles	
Netherlands	Utilities: energy efficiency programmes (stabilising CO2 by 2010), NOx reduction; use of CHP, landfill gas, and renewables	Energy conservation targets for industry sectors	Long-term agreements on energy conservation, insulation, energy-efficient heating in households and for corporations	Energy-efficient fridges, freezers and lighting	Efficient logistics for freight traffic	Monitoring of energy use and GHG emissions
New Zealand	Agreements for CO2 reduction with major energy producers	Corporate energy efficiency commitment campaign and reporting; agreements for CO2 reduction with 15 industry sectors	Limited home energy rating scheme		Agreements on CO2 reduction with major transport companies	Monitoring data disclosure requirements under CO2 reduction agreements
Norway		Energy use reporting for industry groups: Industrial Energy Efficiency Network				
Portugal		Pollution/energy reductions agreements within industry				
Spain	Promotion of fuel substitution, CHP and renewables; DSM for industry	Energy saving targets of industry groups/companies			[Fuel efficiency targets by 1986]	
Sweden	Promotion of CHP production from biofuels; solar heat production, windpower and connections to district heating systems	Corporate commitment for energy-efficient manufacturing and processes	Energy labelling for buildings and homes		Demonstration programmes of alternative motor fuels for vehicle fleets	
Switzerland	Increase of renewables and biomass for energy production	Energy efficiency commitments for industrial energy consumers	Energy efficiency targets for public buildings/hospitals	Efficiency targets and stickers for electrical appliances	15% fuel efficiency targets for cars from 1996-2001	Energy 2000 VA monitoring and reporting
Turkey		(Energy conservation targets for sectors)				
UK	Target for increasing CHP capacity; guidelines for methane reduction from oil and gas facilities	Corporate energy efficiency commitment campaign; Eco-Management and Audit Scheme; agreement for HFC use	Home energy rating scheme	Labelling for fridges/freezers	10% fuel efficiency target for cars by 2005	
USA	Agreements with electric and natural gas utilities for GHG reductions, including methane losses (landfills, and coalbed methane)	Corporate commitments for GHG reductions, energy-saving recycling, and energy efficiency programmes for lighting and electric motors	Labelling for Homes (HERS); Energy STAR Buildings/Homes; "Rebuild America", "Cool Communities" (tree planting)	Efficient lighting for commercial firms & buildings; super efficient refrigerators; high efficiency building, home & office equipment (luminous windows)	Agreements on new generation of motor vehicles; alternative fuel vehicles and refuelling stations	Annual self-reporting of GHG emissions by companies
European Union		Eco-Management and Audit Scheme for companies to reduce CO2 emissions		Eco-labelling scheme for washing machines and dishwashers	(Agreement with car industry on fuel efficiency emissions)	

( ): planned or being proposed; [ ]: phased-out.

(II) The shallow lake's feedback loading mechanism

The following figure offers a similar explanation of the mechanism behind the feedback emission stock loading phenomenon that takes place in a lake. For better understanding assume that the thick snow cover is a thick lay of algae.



Source: Owen O., Chiras D. & Reganold J., (1998), Natural Resources Conservation.

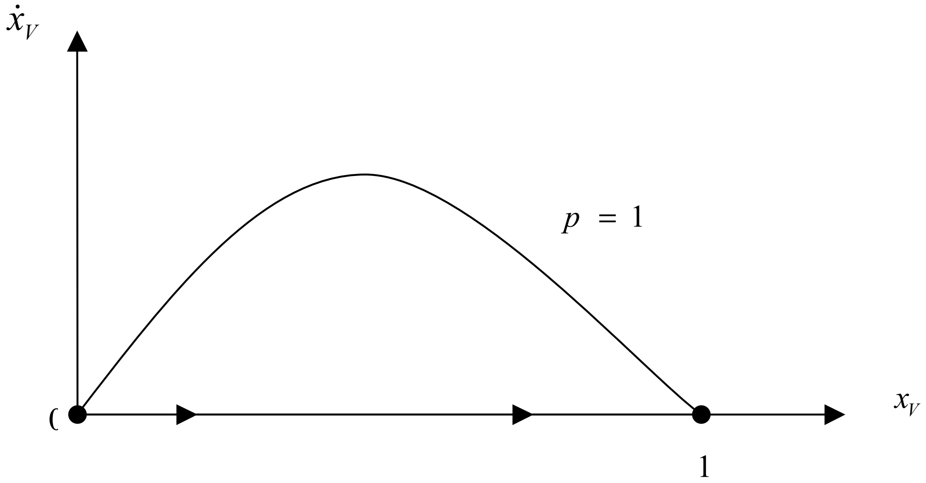


Figure 1a

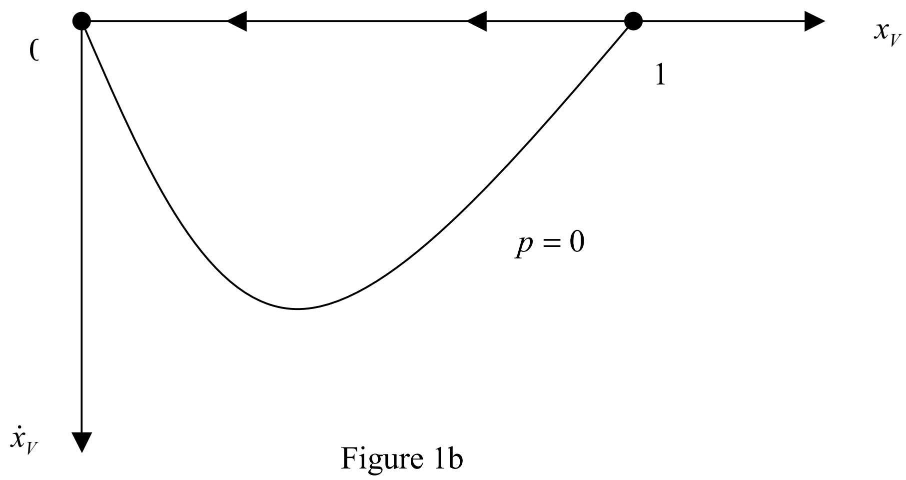


Figure 1b

Figure 1: Equilibrium when emission stock dynamics are ignored.

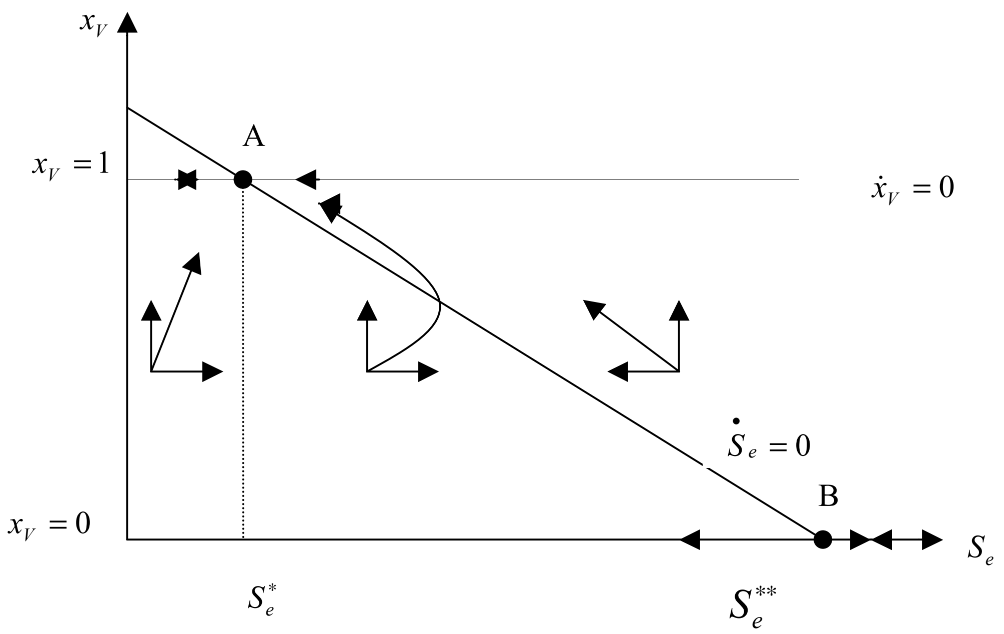


Figure 2a

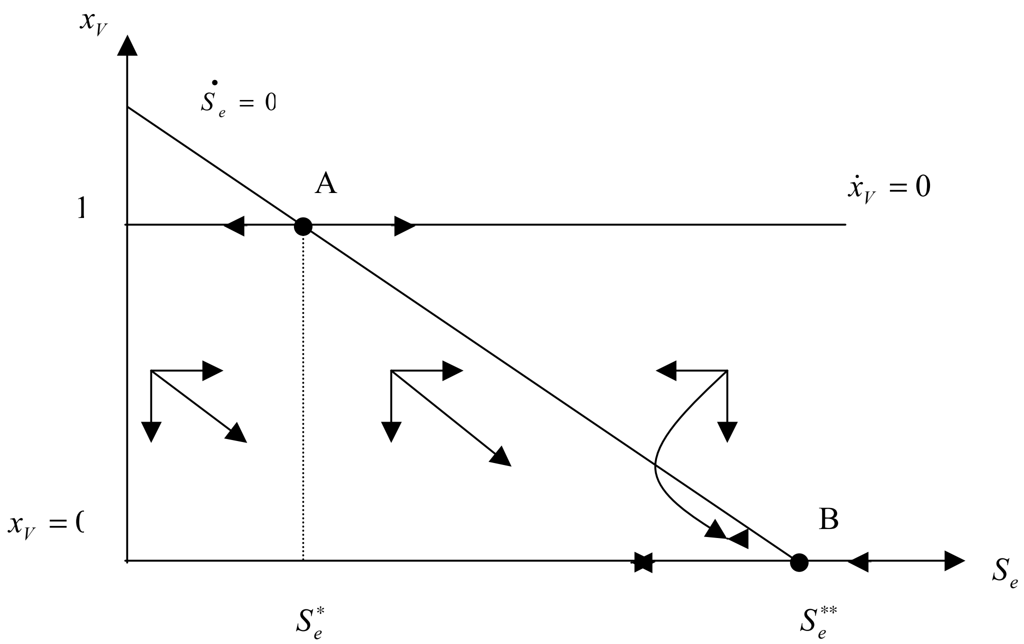


Figure 2b

Figure 2: Monomorphic equilibrium with fixed auditing probability.

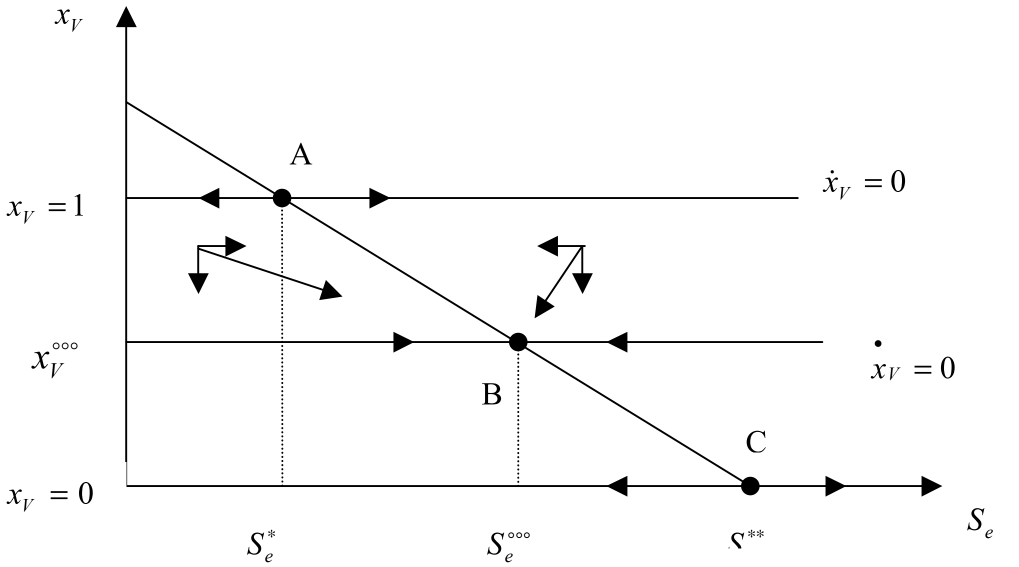


Figure 3a

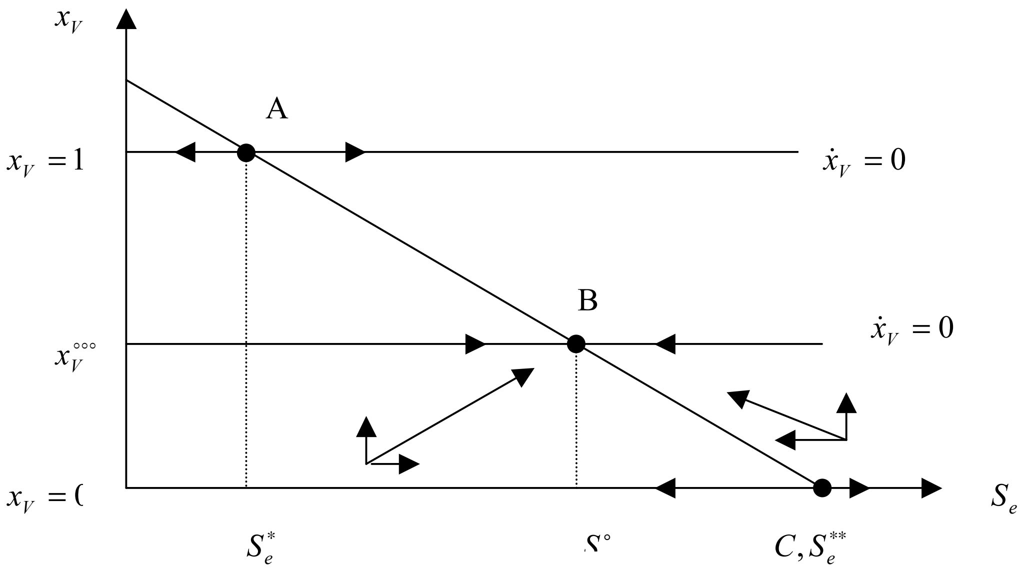


Figure 3b

Figure 3: Polymorphic equilibrium with compliance dependent auditing probability.

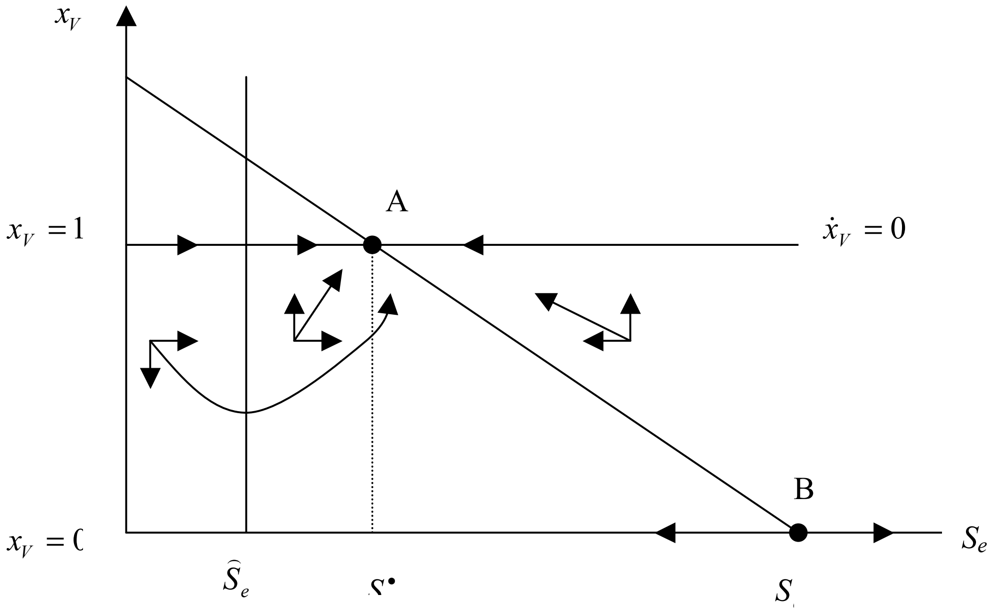


Figure 4a

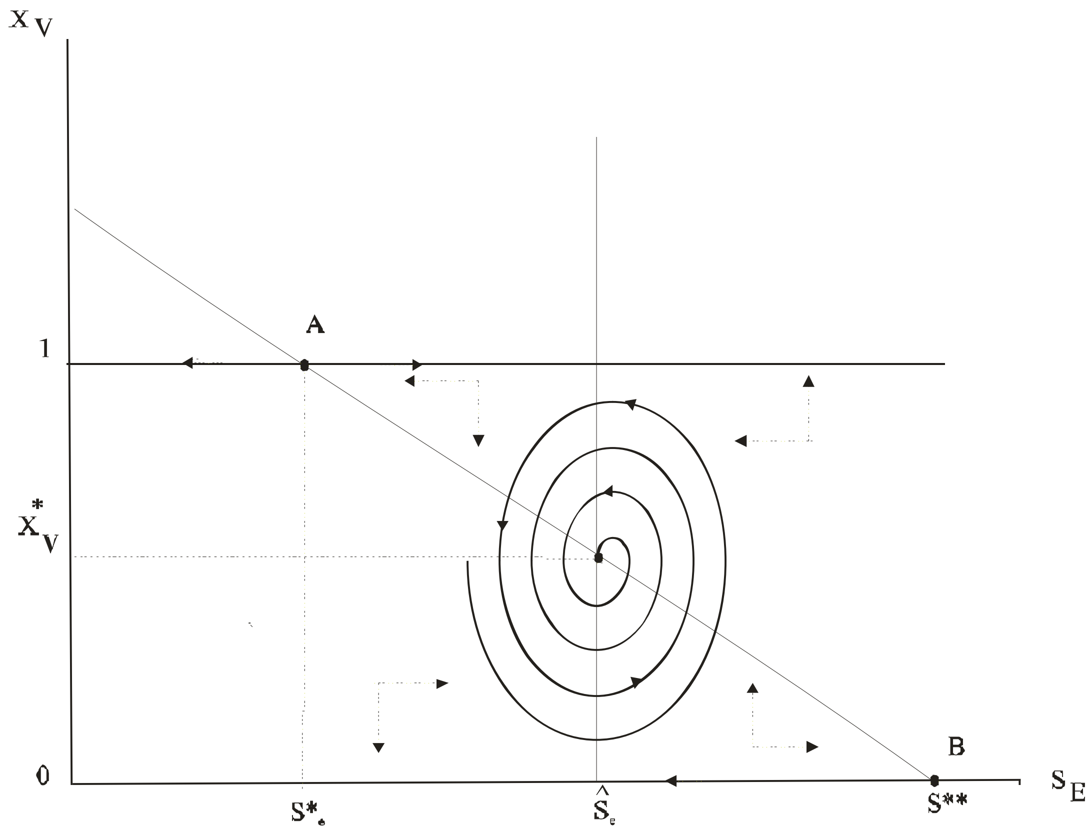


Figure 4b

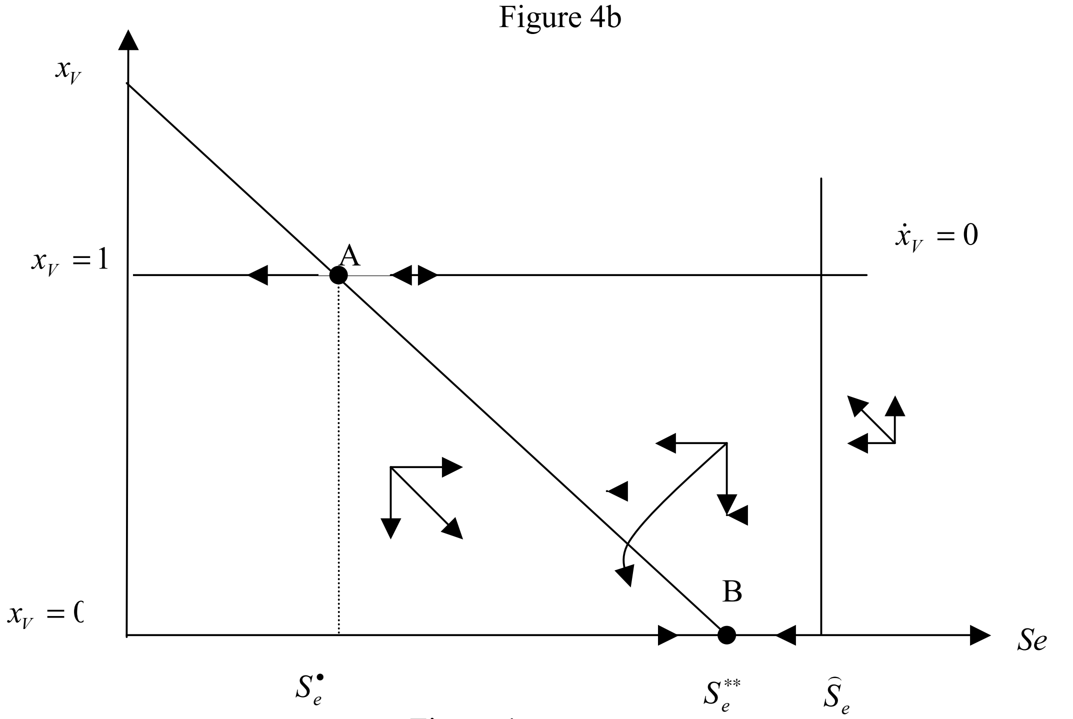


Figure 4c

Figure 4: Equilibrium with emission stock dependent auditing probability.

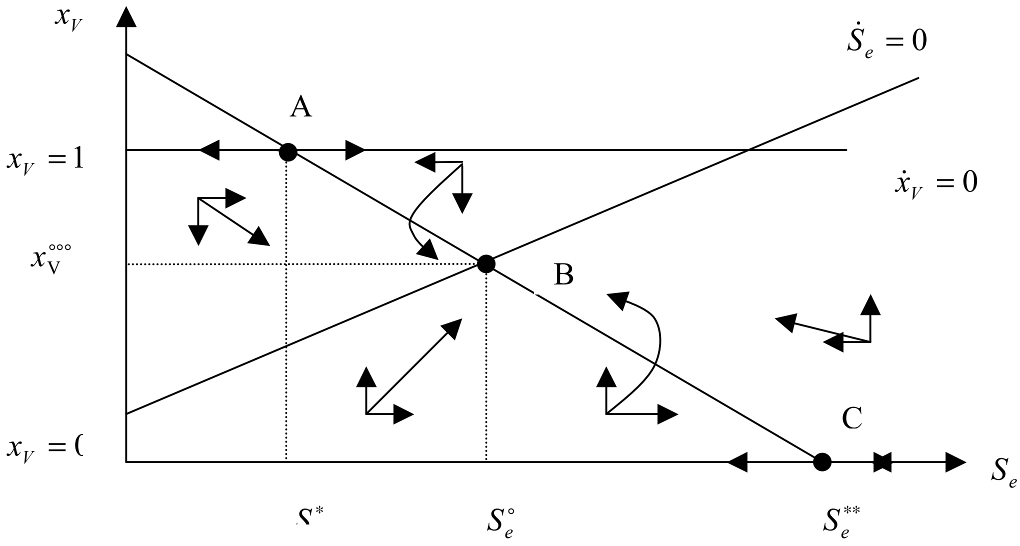


Figure 5a

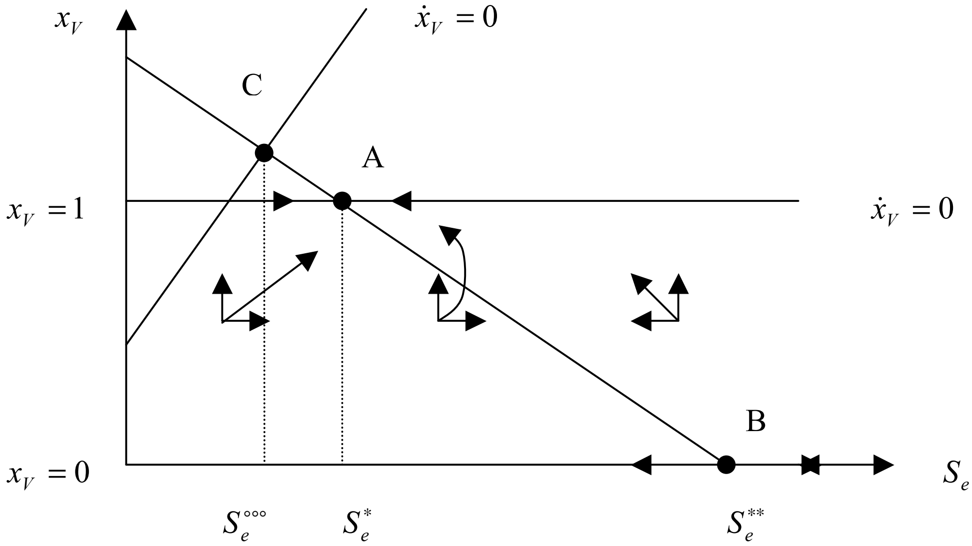


Figure 5b

Figure 5: Equilibrium with jointly dependent compliance and emission stock probability.

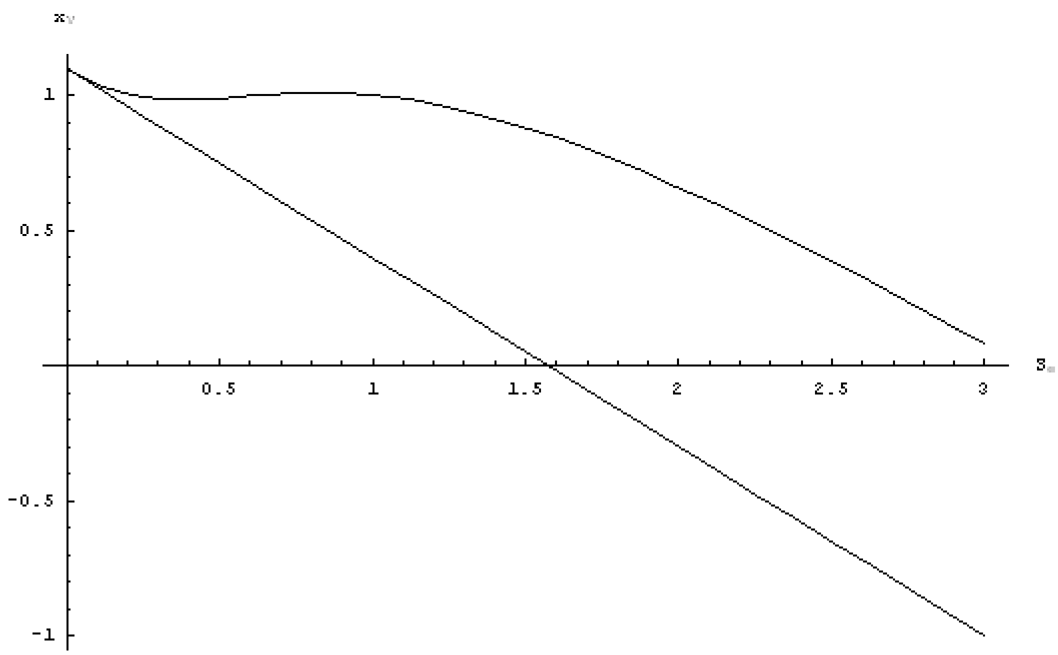


Figure 6: Comparison of emission stock dynamics with linear and non-linear stock evolution.

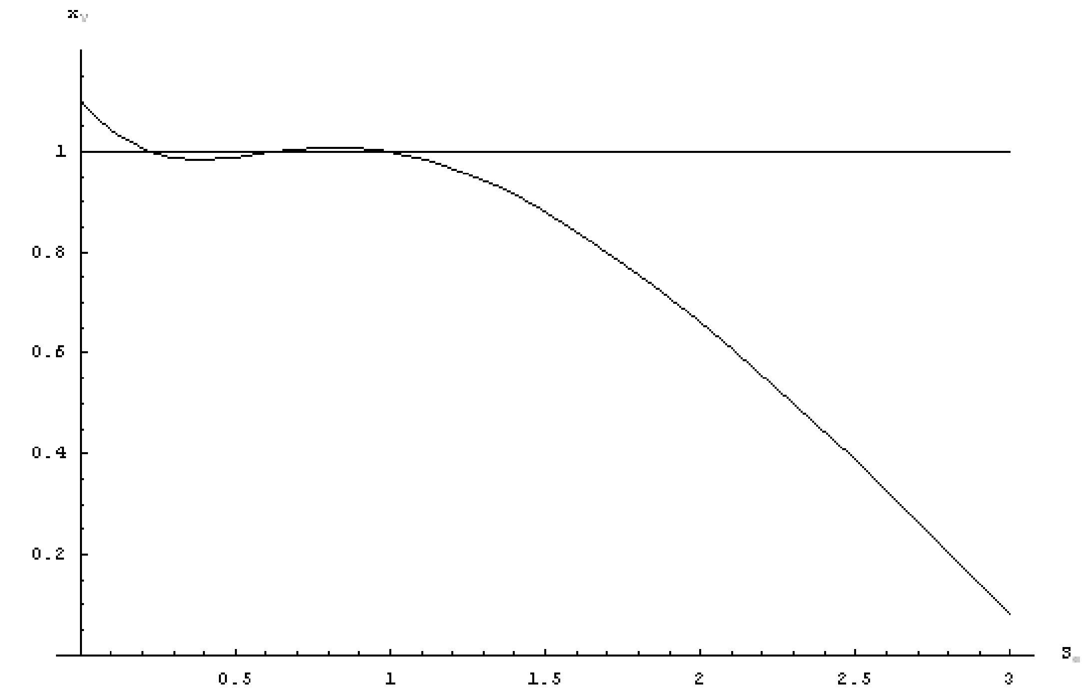


Figure 7: Multiple equilibria with full compliance and non-linear emission stock dynamics.

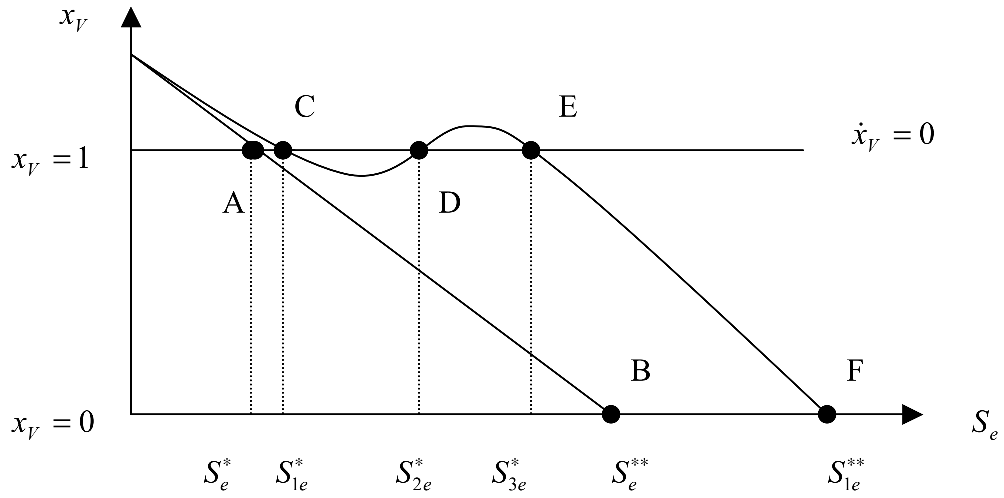


Figure 8a

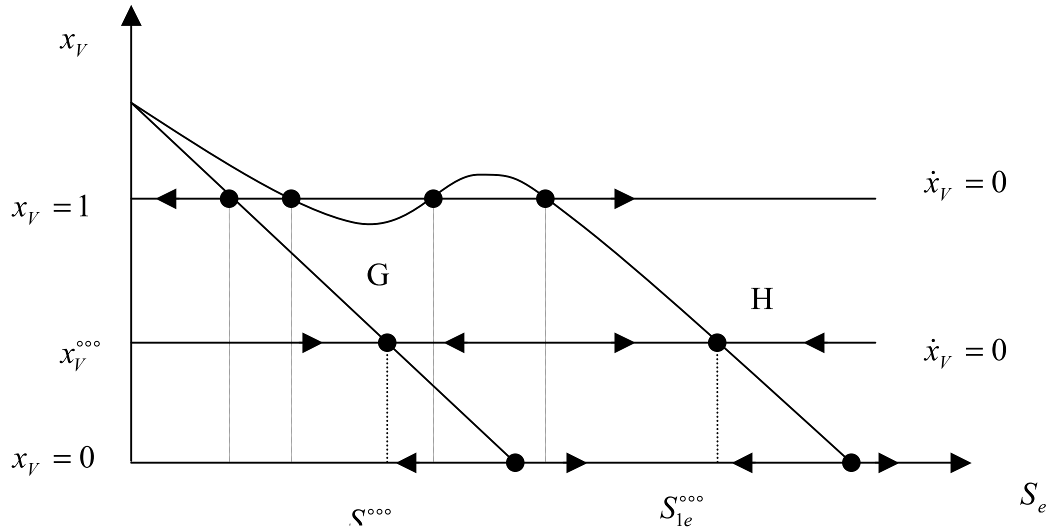


Figure 8b

Figure 8: Equilibrium under non-linear stock dynamics.