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IIASA

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TRADING OF EMISSION REDUCTION COMMITMENTS FOR SULFUR DIOXIDE IN EUROPE

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Foreword

A major new element of international negotiations on further reducing SO_2 emissions is the strive for effect-oriented approaches: environmental susceptibility to pollution should determine the extent of required emission reductions. However, there is no unique link between exposure levels (such as acid deposition) and emission patterns. Atmospheric dispersion processes allow for a wide variety of alternative emission reduction schemes to satisfy the same deposition targets.

Given full information on emission reduction costs, mathematical optimization procedures can be applied to determine cost-minimal solutions. Recently it has been argued that economic instruments (such as e.g. emission trading systems) are able to achieve cost-effective allocations of reduction measures even in the absence of full and centralized information.

An important distinction has to be made between the trading of permits for global pollutants (such as CO_2) and local or regional pollutants (e.g. SO_2). In contrast to global pollutants, reducing the environmental impacts of "local" pollutants depends crucially on the location of measures. Therefore, in order to maintain environmental quality during the process of emission trading, side conditions have to be established for the trading scheme.

This paper makes a first attempt to explore possible schemes for emission trading, taking the regional environmental impacts of pollution into account.

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Director
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Abstract

This paper analyzes the potential role of emission trading systems for non-uniformly dispersed air pollutants, for which the geographical location of emissions has a significant impact on the location and extent of environmental damage. The paper derives the necessary conditions for trading schemes to be cost-effective and introduces the concept of offset rates. Offset rates describe the amount of emissions one source has to decrease if another source increases its emissions by one unit.

To explore the potential performance of alternative trading schemes a simulation framework based on the IIASA-RAINS model has been developed. Simulation runs to achieve regionally specified maximum levels of sulfur deposition (target loads) in Europe show that trading may result in cost savings. The extent to which such cost savings are possible and whether the originally specified target deposition levels are exceeded, depends crucially on the pre-trade level of emissions, the availability of information on costs, and the behaviour of the trading partners. Further analysis is necessary before drawing final conclusions.

Key words: acid rain, sulfur deposition, critical loads, Europe, abatement strategy, cost-effectiveness, emission trading, economic instruments

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1. INTRODUCTION

Currently, negotiations are in progress on a new protocol to control sulfur dioxide emissions in Europe. The present protocol calls for all signatories to uniformly reduce their SO_2 emissions by 30% compared to the year 1980 by 1993. A major new element of the current negotiations is the intention to apply an effect-oriented approach by basing the extent of emission reductions on the susceptibility of natural ecosystems to acid deposition. As a long-term goal, deposition should ultimately be less than so called 'critical loads': the maximum exposure levels that can be tolerated by sensitive ecosystems without damage.

However, a direct conversion of acceptable exposure levels into required emission reductions is not possible. The atmospheric dispersion of pollutants permits a wide variety of possible combinations of emission levels to achieve the same set of maximum exposure levels, such as critical loads. Cost-effectiveness can therefore be introduced as an additional principle to determine the allocation of emission reduction efforts. Cost-effectiveness means that a given environmental objective is reached at minimum pollution control costs.

Several approaches can be applied to identify cost-effective emission reduction strategies. In the past mathematical optimization procedures have been used to derive cost-minimal reduction patterns, assuming full information on the atmospheric dispersion behaviour of pollutants and on emission reduction costs is available (e.g. Amann et al., 1991; Derwent, 1990).

However, the lack of full information in the real world leads to severe doubts about the practical applicability of such optimization approaches. A meeting of designated experts on cost effective implementation of the critical loads approach (Norwegian Ministry of the Environment, 1991) concluded that in view of the inherent uncertainties in the estimation of cost-effective reduction patterns, countries should be given some flexibility to meet their commitments. Economic instruments, such as trading emission permits among countries, could possibly provide powerful mechanisms to approach cost-effective solutions. An additional argument for emission trading is that emission reduction obligations that will result from negotiation might differ from a cost-effective solution since the cost-effective solution may not be regarded as a "fair" distribution of costs among countries.

Over the last few years the use of economic instruments has gained attention as a way to meet environmental constraints in cost-effective ways. In particular, their use played a prominent role in recent international discussions on reducing emissions of greenhouse gases (such as CO_2) (OECD, 1991). However, there is a fundamental difference between reducing such 'global' pollutants and reducing SO_2 emissions. Greenhouse gases accumulate globally, hence the geographical location of emission reduction measures has minor influence on environmental effects. On the other hand, the much shorter residence time of sulfur compounds in the atmosphere means that the ecological impacts are influenced not only by the volume of emission reduction but also on the geographical location of the reduction measures. Although emission trading can keep the total level of emissions constant their location will change. As a result, environmental quality (in terms of concentrations or depositions) will change. Therefore, emission trading has to adhere to (quite strong) side conditions in order to avoid deterioration of environmental quality.

The aim of this paper is to give a broad-brush overview of the types of trading schemes that have been discussed in the literature. After that, a specific scheme, which allows for trading according to a simple offset-rate, is explored. One example of such a rate is based on the marginal costs of emission reductions in an optimal solution. This system is evaluated on cost-effectiveness and environmental performance, and some aspects of the international distribution of costs and environmental impacts are discussed. Further, the potential performance of such a trading system is simulated for the exchange of SO_2 emission permits in order to achieve the target loads for sulfur deposition currently being discussed.

Section 2 describes some of the basic conditions necessary for emission trading schemes to be cost-effective. Section 3 gives an overview of the potential cost-effectiveness and environmental impacts of a number of emissions trading schemes that have been proposed in the literature and applied in practice. Section 4 introduces the concept of offset (exchange) rates and discusses the theoretical merits of such trading systems. Section 5 develops the method to simulate the process of bilateral, sequential trading of emission reduction commitments. Results of some examples (applied to the current European situation) are given in Section 6.

2. COST-EFFECTIVENESS AND TRADING OF PERMITS

2.1 The concept of cost-effectiveness

Whereas the prime objective of environmental policy is the improvement or conservation of environmental quality, the achievement of acceptable levels of emissions, depositions or ambient concentrations is often used as a more practical operational environmental objective. Uniformly dispersed pollutants such as chlorofluorcarbons (CFC) or CO_2 have the same (global) impact on concentrations levels, irrespective of where emitted. In this case, controlling the emissions is sufficient to control the ambient concentration levels. With non-uniformly dispersed pollutants, such as SO_2 or ammonia, deposition or concentration levels are not only affected by the amounts emitted but also by the location of the sources. This spatial aspect complicates both the design of environmental policy in general, and the applicability of emission trading systems in particular.

2.1.1 Controlling emission levels

If the objective of environmental policy can be converted to controlling the total amount of emissions, the necessary conditions for a cost-effective allocation of emission reductions can be derived with the following conceptual framework (Tietenberg, 1985):

A	the total level of emission
e_i	the uncontrolled emissions of source i
r_i	the amount of emission reduction by source i
b	the background emission
A^*	the desired level of emissions
$C_i(r_i)$	the function which represents the minimum costs of each source of reducing emissions with the amount r_i

The total level of emission is the sum of the emissions of all sources (i = 1,...,I) plus the background emissions (e.g. from other regions or from natural sources):

$$A = \sum_{i=1}^{I} (e_i - r_i) + b \tag{1}$$

Cost-effectiveness occurs if the allocation of emission reductions among the sources is chosen such that the costs of reaching the desired level of emission is minimized, subject to the condition that the sum of emissions and background emissions is smaller than or equal to the desired level of emission:

$$\min \sum_{i=1}^{I} C_i(r_i) \tag{2}$$

subject to

$$\sum_{i=1}^{I} (e_i - r_i) + b \leq A^* \tag{3}$$

The most important of the necessary and sufficient (Kuhn-Tucker) conditions for an optimum solution is the following:

$$r_i \left[\frac{dC_i(r_i)}{dr_i} - L\right] = 0 \tag{4}$$

In Equation (4) L is the Lagrange multiplier or the shadow price, which reflects the change in the value of the objective function (in our case the decrease in costs) when the constraint on the desired level of emission is relaxed with one unit.

Equation (4) is a necessary but not a sufficient condition. Further conditions are:

- total emissions should be smaller or equal to the emission target (Equation 3),
- the emission reductions as well as the Lagrange multipliers have to be non-negative,
- the sum of the emissions, including the background, has to equal the objective, otherwise the Lagrange multiplier is zero. (In this case no emission control would be needed to meet the objective.)

The interpretation of Equation 4 is as follows. In an optimum the marginal costs of each source are either equal to L or the source does not have to reduce its emissions (r_i is zero) [1]. The important conclusion is that for the optimal solution the marginal costs per ton of emission control for each source have to be equal.

A trading system for emission permits could be designed in the following way: an emission permit is defined in terms of an allowable emission rate (e.g. tons SO_2) per year. A (central) environmental agency, responsible for the overall pollution control policy of a region, determines the total amount of issued permits (Q) by taking the emission objective

[1] The latter can be the case if the marginal costs of reducing the first unit of emissions for that specific source are rather high.

and subtracting the (expected) background emissions. The permits are then distributed to the sources, e.g. according to emission levels in the past ("grandfathering") or through auction.

It can be shown that under a number of restrictive conditions, trading of such emission permits can attain the cost minimum allocation of resources. The conditions are that sources minimize their pollution control costs (i.e. the sum of expenses for abatement measures and of the net result of trading emission permits), that the permit market is competitive and that information or transaction costs are negligible.

Let's define the following additional elements:

Q the total amount of issued permits

Q_i the initial permits of source i

P the price of the permit

The goal of each individual source is to minimize costs. Costs consist of pollution control costs plus the cost of buying additional permits:

$$\min \sum_{i=1}^{I} C_i(r_i) + P[(e_i - r_i) - Q_i] \tag{5}$$

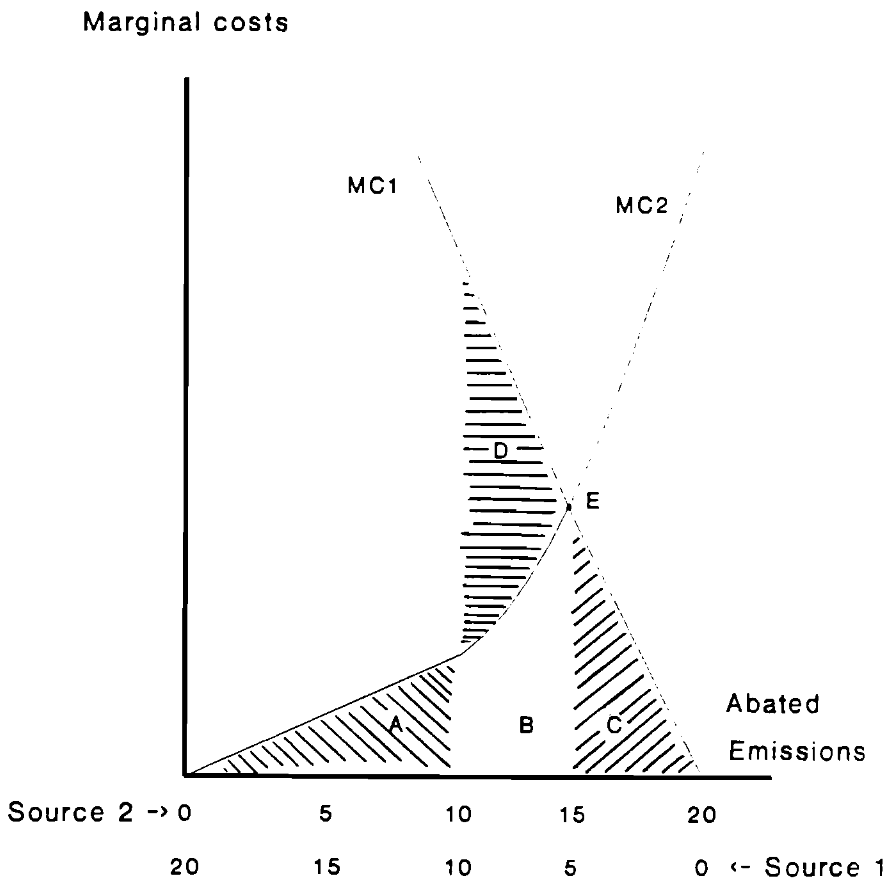
The cost minimum occurs if marginal costs of emission reductions equal the price of the permit. Under perfect market conditions there will be only one price, leading to equal marginal costs for all polluters. Note that this is exactly the condition for a cost minimum in the formulation before. At the same time, the emission ceiling will be met (if enforcement works properly) since no more permits are issued than the total emission objective allows for (Equation 3).

A more intuitive understanding of this cost-minimum can also be given. Figure 1 shows the marginal costs curves of two sources as a function of the reduced emission amount. Drawn in this particular manner, the figure shows all possible combinations of emissions after controlling the two sources which leads to a total emission reduction of 20 units. The allocation of emission reductions that minimizes costs is point D. In this point total costs are the surface A+B+C.

If the initial solution is a uniform reduction (Point E), each source would initially emit 10 units. With emission trading, Source 1 would buy permits for 5 units and thereby reduce its emissions with only 5 units. Source 2 would sell 5 units and thus increase its volume of abated emissions to 15. The total cost savings achieved by both sources equals surface D.

If the market works perfectly, the advantages are plentiful: the cost minimum is attained, the emission objective is reached, no centralized information on pollution control costs is required, and the permits can be distributed initially in any way that is politically acceptable. The agency, however, would have to organize the market.

Figure 1. Emission trading



2.1.2 Controlling exposure levels

When the objective of environmental policy is to attain certain exposure levels (such as ambient concentrations or deposition of pollutants), the control problem becomes more complicated, in particular if more than one receptor is considered (Bohm and Russel, 1985).

In such a case, when the location of emission sources is of importance, the conditions for an optimum solution are different from the simple emission-oriented approach (Tietenberg, 1985). For the conceptual framework the following additional elements are defined:

D_j the level of deposition at receptor j

b_j the background deposition at receptor j

D_j^* the desired level of deposition (the target load) at receptor j

a_{ij} a (linear) transfer coefficient which translates emissions of source i in deposition at receptor j

The deposition at a specific location is a function of the background deposition plus the sum of the emissions, multiplied by their transfer coefficients:

$$D_j = b_j + \Sigma_{i=1}^{I} a_{ij} (e_i - r_i) \qquad (6)$$

This relation applies to every receptor j (j = 1,...,J).

The cost-effective solution requires that the total costs of emission reductions are minimized, subject to the constraint that the desired deposition levels are met at each receptor point:

$$Min\ \Sigma_{i=1}^{I} C_i(r_i) \qquad (7)$$

subject to

$$b_j + \sum_{i=1}^{I} a_{ij}(e_i - r_i) \leq D_j^* \quad \textit{for every } j=1,\ldots,J \tag{8}$$

In addition, the emission reductions have to be non-negative.

The most relevant of the necessary and sufficient (Kuhn-Tucker) conditions for a cost minimum are the following (Tietenberg, 1985):

$$r_i \left[\frac{dC_i(r_i)}{dr_i} - \sum_{j=1}^{J} a_{ij} L_j\right] = 0 \tag{9}$$

$$L_j \left[D_j^* - b_j + \sum_{i=1}^{I} a_{ij}(e_i - r_i)\right] = 0 \tag{10}$$

Equation 10 applies to every receptor (j = 1,...,J).

Further conditions are:

- emission reductions and Lagrange multipliers must be non-negative,
- deposition at each receptor has to be equal or less than the targets (Equation 8),
- marginal costs per ton of emissions removed have to be equal or higher than the sum of the shadow prices for each receptor affected by that source.

The interpretation is as follows. Equation 9 states that for a cost-effective solution either the emission reduction of the source has to be zero ($r_i=0$) or the marginal costs of emission reduction for each source have to equal the weighted sum of the shadow prices (L_j) for each receptor. Weights are the transfer coefficients from source i to each affected receptor j. Equation 10 shows that either the required target load (D_j^*) is met exactly or the L_j (the shadow price) is zero. The latter means that the receptor is non-binding. The important conclusion here is that, generally, for a cost-efficient solution the marginal costs per ton emission reduction will be different.

A system of transferable permits would in this case require the creation of 'ambient permits' or deposition permits. Such permits would allow each polluter to deposit a specific amount at certain receptors. Again the task for an agency controlling the trading would be relatively easy: For each receptor the target deposition level would be specified (based on ecological, political or other considerations). After subtracting background deposition the remaining deposition at each receptor would then be distributed as deposition permits to each polluter. The only information required would be source-receptor matrices describing the atmospheric dispersion of pollutants. For every receptor a separate market would have to be established.

In order to emit one unit each source would have to keep the appropriate number of deposition permits (according to the source-receptor matrix) for each receptor it affects. If a source wanted to increase emissions it would have to obtain additional deposition permits for each of the receptors.

It has been shown that, in principle, the conditions for a cost-minimum solution also satisfy the conditions for a competitive market equilibrium, irrespective of any initial distribution of deposition permits (Montgomery, 1972), if sources are cost minimizing agents. However, there is less guarantee that the markets will be competitive than in the emission related case: every source has to collect a "portfolio" of deposition permits, which requires simultaneous buying in a large number of markets. If the source fails to buy deposition permits for only even one receptor, its emissions cannot be increased. This is likely to imply high transaction costs and complex trading among more than one buyer and seller. Consequently, the number of market participants will be low and a full competitive market cannot be expected.

In conclusion, a system of tradeable deposition permits guarantees achieving deposition targets, but high transaction costs will probably reduce the number of profitable trades and prevent attainment of the cost minimum solution. Information costs and administrative burden are relatively low for the agency although atmospheric transfer matrices are necessary to determine the allocation of deposition permits. The administrative burden is relatively high for the sources since trading will be complex.

3. ANALYSIS OF ALTERNATIVE TRADING SCHEMES

3.1 Alternative trading schemes

In view of the difficulties encountered in establishing a complete set of properly functioning markets for deposition permits, several alternatives have been suggested in the literature in order to attain deposition targets or ambient standards:

1. Trading of emission permits within one zone.
2. Trading of emission permits within several zones.
3. Single market deposition permit system.
4. Emission trading subject to trading rules.

3.1.1 Emission trading in one zone

The system described in Section 2.1.1 could be established for trading emission permits within one zone. Such 'single zone' trading implies that pollution control costs would be minimized for (initial) total emissions. However, Bohm and Russel (1985) show that such trading systems:

- would either not meet the deposition targets (if the initial amount of emission permits is too high so that after trading targets will be violated at some receptors),
- or the costs would be higher than the cost minimum (if no conceivable set of trades is to violate the standards, initial emissions have to be lowered such that after trading standards are not exceeded).

Clearly, single zone trading cannot be cost-effective since it tends to equalize marginal costs, whereas marginal costs generally have to be different if a set of deposition targets is the environmental objective. The system could be cheaper or more expensive than uniform percent reductions. This depends on the specific regional situation, i.e. the actual transfer coefficients, the cost functions and the levels of unabated emissions of sources (Russel, 1986). The major advantage is that the system is simple; administrative practicability is high and transaction costs will be low.

3.1.2 Emission trading in several zones

Trading emission permits among several zones has a certain surface appeal. It offers more protection for deposition targets than emission trading in one zone and reduces control costs. However, this is only the case if the environmental agency has complete and correct knowledge of emission control costs. With limited information, the cost will be higher than the cost minimum since emissions cannot be traded among zones. This being so, since without knowing the cost-minimum solution, the environmental agency does not know how many permits it should allocate to each zone. In addition, there would be no protection against violation of the standards even in small zones (Tietenberg, 1985) since it is not exactly known where emissions take place after trading.

3.1.3 Single market deposition permit systems

Single market deposition permit systems focus on one single "worst case" receptor (a 'hot spot'). This type of trading might come very close to the cost minimum. In the absence of multiple binding constraints and a stable geographical distribution of emitting sources, it also allows for a high degree of control of ambient standards. However, if more receptors are binding, trading deposition permits for only one of them is likely to violate the deposition standard for the other binding receptors. If the geographical distribution changes, other receptors than the single "worst case" receptor may become receptors where the deposition targets are violated. Since the focus is on only one receptor it will inevitably create an incentive for sources to move to regions where the impact on the hot spot is restricted. Consequently, new hot spots will be created undermining the selection of the initial "worst-case" receptor (Tietenberg, 1985).

3.1.4 Emission trading subject to trading rules

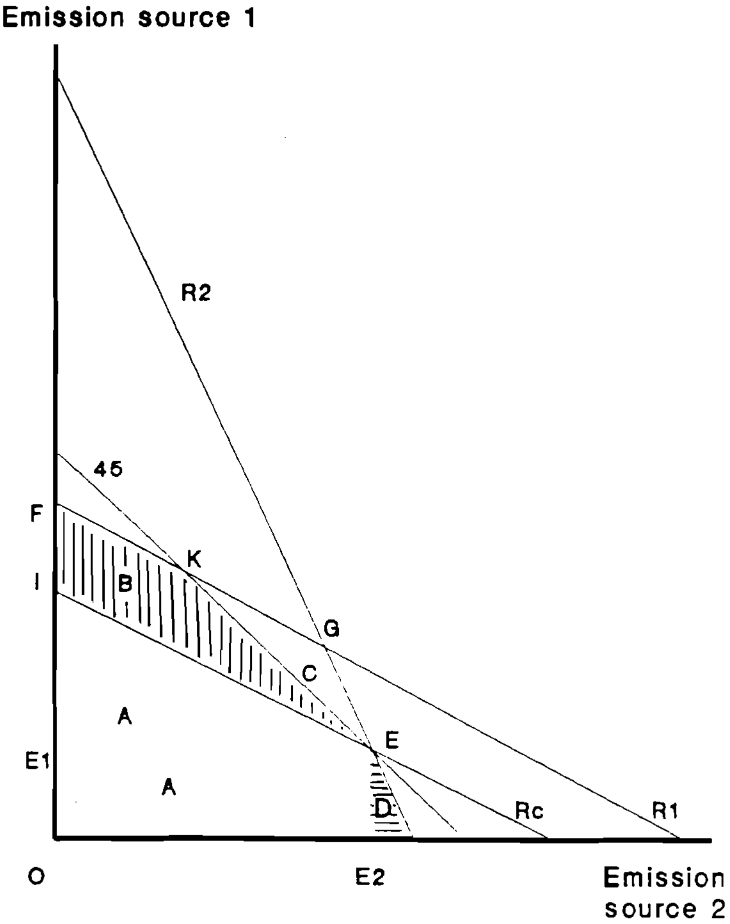
Three rules for trading subject to rules have appeared in the literature (Atkinson and Tietenberg, 1982; Krupnick et al., 1983; McGartland and Oates, 1985; Tietenberg, 1985):

1. 'Pollution offset' (trading subject to the condition that the deposition targets are not violated).
2. 'Non-degradation offset' (trading subject to non-violation of deposition targets plus the fact that total emissions are not allowed to increase).
3. 'Modified pollution offset' (subject to deposition targets and pre-trade air quality).

The first rule (pollution offset) appears the most promising, offering the largest potential for cost savings with the least binding restrictions. Rule two, the 'non degradation rule' comes very close to the US EPA emission trading program of 1986. The third rule, 'modified pollution offset' prevents deterioration at receptors where pre-trade air quality is already better than the standards because neither the deposition targets nor the pre-trade air quality are allowed to be violated. These rules do not force sources to trade according to a fixed rate e.g. on a one-to-one basis. In principle, the ratio at which sources exchange their emission permits is free as long as the ambient standards are not violated. This requires a diffusion model which shows that air quality standards are not violated before and after each trade.

Figure 2 shows how these rules would guide trading. There are two receptors R1 and R2. The starting point is E. RC is the line that represents the pre-trade (current) air quality at receptor 1. The 45 degree line presents the combinations of emissions that hold the emissions constant.

Figure 2. Different trading rules



If Source 2 is the first source to sell permits (thereby decreasing its own emission), under the pollution offset rule the trading possibilities would be within the area A+B+C. This is since neither the ambient standard for receptor R1 nor for receptor R2 may be violated. So emissions should stay left from the line FG/E2. Under the non-degradation offset rule trading possibilities would be limited to A+B, since emissions:

- are not allowed to increase (should remain left from the 45° line)
- are not allowed to violate the ambient standards at receptor R1 and R2.

This limits the trading area to the area left from the line FKE/E2. The modified pollution offset rule would restrict trading to A only, because neither the pre-trade air quality (RC) nor the ambient standards for receptor 1 and 2 may be violated. So trading should take place left from the line IE/E2. If Source 2 buys permits (increasing its emissions) the trading area would be limited to area D for all rules, since receptor R2 is then the binding constraint for all rules.

Hence the pollution offset rule offers the largest potential for cost savings since it does not make trade contingent on the pre-trade situation of the two sources. Because trading can take place in the whole area A+B+C+D, the optimum situation can be attained without violating the deposition standards. However, Tietenberg (1985) mentioned that the following two effects might occur:

1) Any actual sequence of trading might be unable to capture the full cost-potential.
2) For some trades the ratio of emission increases is not adequately defined: some sources might be able to increase emissions without compensation ("free riding").

Only if simultaneous trading occurs is the system supposed to be fully cost-effective. If trading is sequential it would have to be repeated; some trades may even have to be reversed in order to achieve the cost-minimum. In general, the fact that trading is bilateral rather than simultaneous applies to every trading scheme that tries to take account of deposition targets. Bilateral trading does, therefore, restrict the cost-savings we can expect from trading (Atkinson and Tietenberg, 1991).

In summary, the offset-rule appears to offer the largest potential for cost-effectiveness, followed by the non-degradation offset. All rules guarantee achieving target loads.

All the above trading rules have a drawback to attaining the cost minimum solution: trade ratios are not simple, fixed ratios but are contingent on the pre-trade emissions of all sources and target loads. A second problem is that after every trade, the possibilities for other sources to trade change since, in order to not violate the deposition targets, they depend crucially on the emissions of all other sources. Systems taking this aspect into account become more complex, at least for the traders, and air quality or dispersion modelling is required to evaluate the impact of each trade on the desired deposition levels. In other words, the potentially larger gains and the increased certainty that deposition targets will be met has a price in the form of higher transaction costs. For the central authority, however, the task is still relatively simple. No knowledge of costs is required. The agency can ask the trading partners to run air quality models to prove that deposition levels after the trade are not worse than before.

3.2 Rules for emission trading in the USA

The emission trading program of the US Environmental Protection Agency (EPA) is strongly based on trading rules, especially on the non-degradation offset rule. This system does not allow emissions to increase and national ambient standards may not be violated. Within the constant emissions rule, different states are allowed to have their own interpretation. Generally, a demonstration of air quality before and after the trade is required.

The EPA's emissions trading policy statement describes emission trading and sets out general principles for evaluating emission trades (Borowsky and Ellis, 1987). The policy statement consists of eight parts: covered air pollutants, sources allowed to be traded, ways to trade, definition of emission reduction credits, definition of baseline emissions, use of credits, air quality tests and state specific trading rules. All air pollutants for which there are national air quality standards (concentrations in the air) can be traded among all existing and major new stationary sources.[2]

The most important trade systems are the 'bubble concept' and the 'offset rule'. Bubbles allow existing sources to increase emissions as long as other sources decrease them. The offset rule applies to new sources. It allows new or modified sources to use an offset (reduction in emissions) from existing sources as long as progress is made in attaining air quality standards in non-attainment areas where air quality is worse than the standards. In the case of attainment areas air quality standards may not be violated and significant deterioration has to be prevented. Emission reduction credits (ERC) are surplus emission

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[2] A recent amendment of the US Clean Air Act, requiring a ten million ton reduction in SO_2 emissions, will be implemented through a national emission trading system. All of the USA is considered one zone. It is based on the premise that given the reduction, ecosystems will be protected regardless of which particular sources are controlled to what specific degree (Kete, 1991).

reductions currently not required by law. They are enforceable, quantifiable and permanent. An ERC cannot be used to avoid emission standards for new sources.

Emission trades for SO_2, amongst others, must satisfy an ambient test. Such ambient tests check for a non-significant impact of an emission trade on air quality (i.e for SO_2 less than 1 to 3 microgram SO_2/m^3 as annual average). There are four methods for determining ambient equivalence:

1. Minimis: if emissions are constant and the sum of the increased emissions from the increasing source is less than a certain level no air quality test is needed.
2. Air quality modelling is not required if emissions are constant and sources are located within 250 meters.
3. Limited air quality modelling of only those sources trading is needed if total emissions are constant and no significant air quality impact occurs.
4. Full air quality modelling is needed if there is a net increase in emissions or if the trade produces a significant impact on air quality.

Finally, states may adopt alternate generic trading rules that assure attainment and maintenance of air quality standards.

According to a selective overview by Hahn (1986) some states do, others do not (always) require dispersion modelling to demonstrate air quality before and after trading. States appear to have interpreted EPA's trading rules to guarantee against exceeding air quality standards in three ways:

1. Requesting offset ratios bigger than one to ensure that overall emissions will be reduced (California, Idaho).
2. Limiting trades to relatively small zones, minimizing the occurrence of hot spots (California, New Jersey).
3. Requiring dispersion modelling (Illinois, Indiana, Virginia, Connecticut).

Emission trading has been practiced in the USA for more than a decade. There seems to be agreement that trading results in (considerable) cost savings and has a neutral to positive impact on the environment. However, there also appears to be consensus that trading is less cost-effective than economic theory and simulation models would have us believe. Creating a market de-novo is not easy: some 80 % of the observed trades have been internal (within a firm) rather than external. Several arguments have been given to explain the lower than expected cost savings:

- emission trading is combined with existing regulations (e.g. new sources still require reasonable available control technology) thus limiting trading possibilities (Hahn and Hester, 1989);
- statutory provisions restrict trading (e.g. diffusion modelling requirements and complicated rules for external trades) (Tietenberg, 1989; Hahn and Hester, 1989);
- transaction costs are high (searching for trading partners, costs of obtaining approval);
- uncertainty about the nature of the property rights (i.e. fear of confiscation of created rights) restricts supply of emission permits (Hahn and Hester, 1989);
- demand for emission permits is limited: old sources already have equipment installed or are not pressured too hard, new sources have to meet standards anyway;
- excess emission reductions are created (and could be sold) but for strategic reasons are hoarded for future, internal use (Dwyer, 1991);
- trading is bilateral and sequential rather than simultaneous so the theoretical cost minimum is not attained (Atkinson and Tietenberg, 1991).

In conclusion, an assessment that aims to give a realistic picture of the potential cost-savings of emissions trading has to account for the above elements. Furthermore, in developing future trading schemes one should be aware of these elements.

3.3 Conclusions on emission trading schemes

Several possibilities for trading permits exist that might, in principle, be used to maintain the environmental objective of attaining deposition target levels and still allow emission sources sufficient flexibility to save costs (and thereby valuable resources). However, trade-offs are involved with every system.

Systems that promise large cost savings, in theory, and attainment of the deposition targets may be complex for potential traders, which might limit their cost-effectiveness in practice. These types of emission trading schemes are:

- trading of deposition permits,
- trading subject to trading rules in the form of attaining deposition targets (some of them in combination with constant-emissions).

More simple schemes are at least in theory less cost-effective and although they do not give a guarantee that deposition targets are met they require lower transaction costs. Hence, more vivid trading and higher cost savings can be expected in practice:

- trading of emission permits within one zone,
- trading of permits within several zones,
- trading based on (fixed) offset rates.

In the United States emission trading is allowed by the new Clean Air Act and the EPA Guidelines of 1986 required dispersion modelling and the guarantee that emissions do not increase after trading. Several US states have specified their own interpretations to limit the probability for "hot spots" such as: offset rates bigger than one, trading in small zones and dispersion modelling. The 1990 amendments of the Clean Air Act, however, allow emission trading for SO_2 in one zone (the USA).

None of the systems is perfect however, and trade-offs between cost-effectiveness, environmental effectiveness (extent to which the environmental objectives, such as deposition targets, are met), administrative complexity and political acceptability seem to be unavoidable.

4. EMISSION TRADING USING OFFSET RULES (EXCHANGE RATES)

4.1 The concept of offset rules

As shown in the previous section, an alternative trading system, which is relatively simple and applied in practice, is emission trading subject to an offset rate. An offset rate or exchange rate is defined as:

> 'the volume of emissions that one source has to decrease if another source increases its emissions with one unit'.

In other words, the exchange rate states that if one source increases emissions by one unit (it buys emission permits) another source has to decrease its emissions by the same amount multiplied with the exchange rate (it will then sell permits).

A small model will helps to structure the problem. The following elements are defined:

E^0_x	pre-trade emissions of source x
E^0_y	pre-trade emissions of source y
E^1_x	post-trade emissions of source x
E^1_y	post-trade emissions of source y
T_x	the change of emissions of source x as a result of trading
T_y	the change in emissions of source y as a result of trading
W_{xy}	the exchange rate (the rate at which y has to decrease emissions if x increases emissions with one unit)
$C_x(E_x)$	the function which represents the costs to source x of reducing emissions to E_x.
$C_y(E_y)$	the function which represents the costs to source y of reducing emissions to E_y.

Both cost functions are represented as functions of the remaining emissions after abatement.

Assuming that both sources want to minimize costs the problem can be stated as follows:

Minimize: $C_x(E_x) + C_y(E_y)$ **(11)**

subject to:

$E^1_x = E^0_x + T_x$ **(12)**

$E^1_y = E^0_y - T_y$ **(13)**

$T_y = W_{xy} * T_x$ **(14)**

All volumes are non-negative, W_{xy} is positive.

The conditions (12) to (14) can be reformulated as one condition by substituting (14) in (13). Then we eliminate the traded amounts (T_x and T_y). After shifting pre-trade amounts of emissions to the right hand side, post-trade emissions to the left hand side, and dividing by W_{xy}, we obtain only one condition:

$E^1_x + E^1_y/W_{xy} = E^0_x + E^0_y/W_{xy}$ **(15)**

Using Equations (11) and (15) we have the classical problem of programming subject to an equality constraint (Intriligator, 1971). The solution to this problem can be found in formulating the so called Lagrange function L:

$L\ (E_x,E_y,L): C_x(E_x) + C_y(E_y) + L\ \{(E^0_x + E^0_y/W_{xy}) - (E^1_x + E^1_y/W_{xy})\}$ **(16)**

with L being the Lagrange Multiplier. The conditions for a cost-minimum solution (Intriligator, 1971) are the following:

$\delta C/\delta E_x = 0 \quad <=> \quad C_x'(E_x) - L = 0$ **(17)**

$\delta C/\delta E_y = 0 \quad <=> \quad C_y'(E_y) - L/W_{xy} = 0$ **(18)**

$$E^1_x + E^1_y/W_{xy} = E^0_x + E^0_y/W_{xy} \tag{19}$$

in which the suffix ' of the cost functions indicates marginal costs. Conditions (17) and (18) can be combined by eliminating L:

$$C'_x(E_x) = W_{xy} * C'_y(E_y) \tag{20}$$

In this case the following situations are possible:

- If in the pre-trade situation $C'_x(E_x) > W_{xy}*C'_y(E_y)$, then country x profits by paying country y to purify more and itself increase its emissions.

- If in the pre-trade situation $C'_x(E_x) < W_{xy}*C'_y(E_y)$, then it pays for country x to reduce emissions further (hence increase marginal costs) and allow country y to increase emissions.

The condition of Equation 20 can be interpreted as follows: If $W_{xy} = 1$, we have the classic condition for an optimum stating that marginal costs of both sources have to be equal. If W_{xy} is unequal to one (e.g. $W_{xy} > 1$), and initially the marginal costs of x > W_{xy}* marginal costs of y, then the offset rate implies that source y will have to decrease its emissions more than source x is allowed to increase them. Accordingly, it is more difficult for source y (it requires more efforts, hence more costs). To compensate for the fact that emission increases for source x are smaller than the emission reduction required for source y, the marginal costs to source x (in the optimum) have to be W_{xy} times higher than the marginal costs to source y in order to achieve a cost-minimum solution.

In summary, conditions (19) and (20) are the conditions for an optimum solution to the problem of bilateral trading if trading is subject to an exchange rate or offset rate.

4.2 Emission trading with an exchange rate equal to the ratio of the marginal costs in the optimum

One possibility for selecting the offset or exchange rate is to base the exchange rate on the ratio of the marginal costs in the optimum. This rule can be based on the understanding that the ratio of the marginal costs in the optimum depends on the shadow prices (relative difficulties) of attaining the binding deposition constraints. It reflects one of the conditions for a cost-minimal solution (see Section 2, Equation 9). The ratio of the marginal costs (MC_1 and MC_2) of two sources in the optimum is:

$$\frac{MC_1}{MC_2} = \frac{\sum_{j=1}^{J} a_{1j}\, L_j}{\sum_{j=1}^{J} a_{2j}\, L_j} \tag{21}$$

Recall that the L_j's are the Lagrange multipliers (the shadow prices) for the binding receptors. They reflect the marginal costs of tightening the constraints.

To explain how this ratio governs trading we give a simple example with one binding receptor and two sources. Let's assume a transfer coefficient from source 1 to the receptor of 0.5 and from source 2 to the receptor of 1. The following condition then applies in the optimum:

$MC_1/MC_2 = 0.5/1 = 0.5$.

Therefore we take the ratio of 0.5 as the exchange rate $W_{1,2}$. This implies that source 1 would be allowed to increase its emissions with one unit as long as source 2 reduces emissions with 0.5 units.

The advantage of such a rule is that it is simple for the trading sources. However, as will be demonstrated later, there is neither a guarantee that the system will attain the cost minimum nor is there certainty that deposition targets will not be violated, even if the environmental agency has complete and correct knowledge of the costs necessary to determine the trading ratio.

The introduction of such a trade ratio fulfills only one of the several necessary conditions, stating that the ratio of marginal costs should be equal to the exchange rates for a cost minimum (Section 2, Equation 9). The important condition, that deposition is not allowed to exceed target loads (Equation 8), is not a condition for the offset-rate trading. This was a choice made in order to first investigate unconstrained trade due to the complexities of the trading process of imposing target load constraints. Hence, the solutions to both problems are not identical. Mathematically there is no guarantee that the cost minimum will be attained by trading nor that the deposition targets will be met. The initial emissions of the sources and the trade ratios restrict the possible range of solutions that can be reached by trading.

This can be illustrated graphically. The y-axis of Figure 3 shows the emissions of source 2 and the x-axis emissions of source 1. The lines R1 and R2 are combinations of emissions from both sources for which the deposition targets at Receptors 1 and 2 are met with equality, assuming (constant) emissions from all other sources. The curves C1, C2 and C3 are iso-cost curves: they show combinations of emissions from both sources which lead to the same level of total costs. The closer these costs are to the origin, the higher the costs and lower the emissions are. The Figure shows that as long as emissions from both sources remain within the area OAEB the deposition targets are met. The least-cost solution is point E. At this point the ratio of the marginal costs equals the weighted ratio of their transfer coefficients for Receptors 2 and 1, which at this point are both binding. This ratio is also the coefficient that determines the direction of line R3 (weighted between R2 and R1). This implies that an exchange rate based on the ratio of the optimal marginal costs allows both sources to trade as long as they move (trade) along a line parallel to the line R3. We see now that whether the optimum (E) is attained or not depends on the initial solution. If the initial position is P, the trading ratio prevents attaining the optimum, although cost savings are possible. Starting from P, sources would only be allowed to trade along the dotted line R3' (parallel to R3). In this case, E' would be the least cost solution attainable from P with the given trade ratio. Obviously E' is not identical with E, and therefore costs (C2) are higher than in the real optimum (C1).

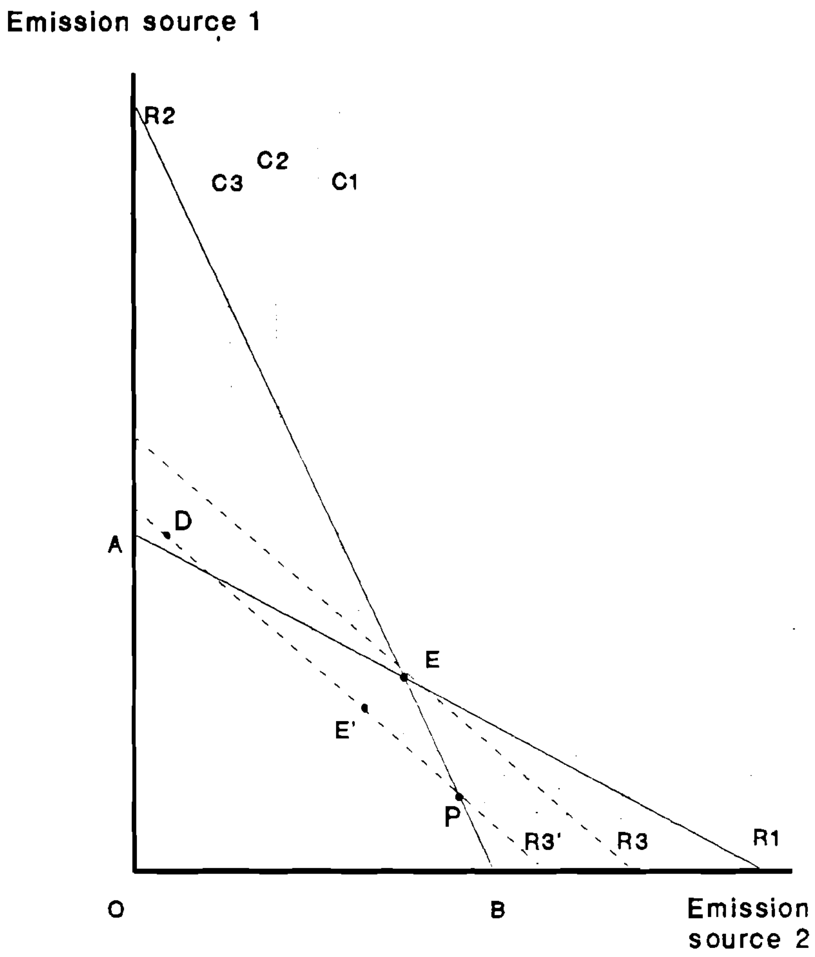
The question arises if trading according to an exchange rate equal to the marginal costs in the optimum can lead to exceedance of the deposition targets. The answer is that this might happen, depending on the configuration of the cost functions, for two reasons:

1. Although the configuration of cost functions is likely to move countries from any initial solution into the interior of the feasible region, there is no guarantee that trading stops inside the feasible region (AEBO).
2. The exchange rate steering the bilateral trades is based on the optimum solution for all cost functions of all countries, whereas the bilateral trade optimum is based on a cost-minimum solution based on the cost functions for the two trading countries only.

Regarding the first reason, Figure 3 shows that for that specific configuration of cost functions source 2 will decrease emissions and we move into the interior of the feasible region up to point E'. Given the iso cost curves it is not possible that we move from P' out of the feasible region to D, since this would increase costs (iso cost curve would be closer to the origin). However, depending on the specific configuration of cost curves and the starting point it is conceivable that we move into the interior but do not remain inside. In this case trading could bring us to point D, outside the feasible region.

The second reason implies that the iso cost curves for the two trading countries are not the same as the iso cost curves for all countries. Consequently, the iso cost curves for the two countries (C_2 and C_3) are not necessarily parallel to the iso cost curve (C_1) for all countries. So in this case the cost-minimum solution for the two countries might be in or outside the feasible region.

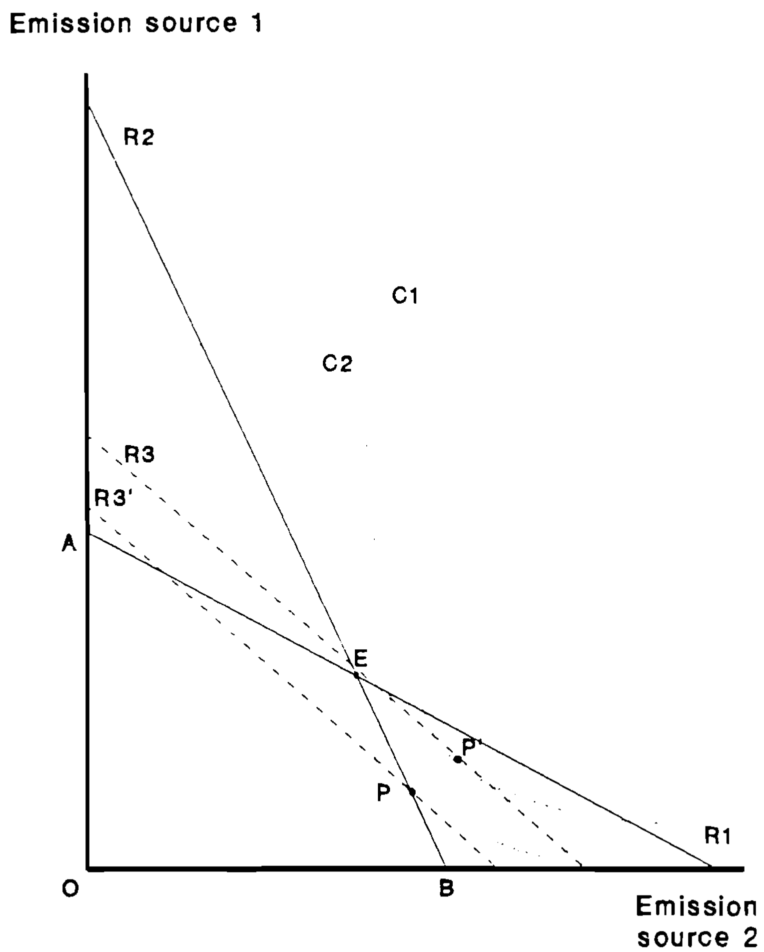
Figure 3. Trading with an exchange rate.



In summary, whether or not the proposed exchange rate brings the optimum depends on the initial solution, even if the costs are known exactly.

If an environmental agency has incorrect information on costs, it is likely that neither the cost-minimum nor the deposition targets will be attained. Sources will trade on the basis of their costs, but the exchange rates would be based on the environmental agency's (wrong) perception of the costs. For illustration assume that the 'real' optimum (based on the 'true' cost curves C_1 and C_2) is Point P (Figure 4). From any starting point trading could only move parallel to R3, since this direction (reflecting the ratios of the marginal costs as they have been assumed by the agency, based on incorrect information on the costs C') is determined as the trade ratio. If we take e.g. E as a starting point, trading would follow the line R3. In this case trading will move us from Point E to Point P', outside the feasible area, since at that point iso cost curves are further away from the origin and costs for both sources are lower.

Figure 4. Incorrect information on costs



Although there is evidence that the optimum solution could be achieved by chance, the question remains of how close such a trading scheme could approach the optimum. Unfortunately, an analytical solution is rather difficult to develop and the magnitude depends crucially on the actual problem specification (transfer coefficients, target loads, cost curves, initial solutions). Therefore, the following section describes a simulation of such trading processes and their application to reducing the long-range transport of sulfur compounds in Europe.

5. THE TRADE SIMULATION: METHOD AND DATA

5.1 Introduction

This section describes the method (algorithm) developed to simulate bilateral, sequential trading using trade ratios as introduced above. In addition, data on the costs and transfer coefficients used for the example simulation runs are briefly summarized.

The algorithm makes use of an adapted version of the optimization module in the RAINS (Regional Acidification INformation and Simulation) model (Alcamo et al., 1990). This model simulates the flow of acidifying pollutants (sulfur and nitrogen species) from source regions in Europe to environmental receptors. The current model (version 6.0) covers 38 source regions in Europe: 26 countries, 7 regions in the former USSR and 5 sea regions (ship emissions). Analysis of deposition is performed for 547 land-based receptor sites with a regular grid size of 150*150 km.

5.2 The optimization approach implemented in the RAINS model

The optimization mode of the RAINS model allows the user:

1. to identify the cost-minimal international allocation emission reduction measures to attain a set of deposition levels for each receptor site in Europe;
2. to determine the lowest costs to attain a target level of total European emissions.

The optimization modules formulate possible strategies to minimize the costs of achieving deposition targets at certain receptors as a linear optimization problem that can be solved with LP packages (Batterman and Amann, 1991). The cost-effective solution requires that the total costs of emission reductions are minimized, subject to the constraint that the desired depositions are met at every receptor:

$$Min\ C = \Sigma_i\ \Sigma_l\ C'_{i,l}\ R_{i,l} \tag{22}$$

$R_{i,l}$ is the emission reduction in region i at the l th level. Cost functions of emission reductions are expressed as piecewise linear curves denoting cost-minimal combination of measures within each country to achieve certain levels of national total emissions. $C'_{i,l}$ are the marginal costs, determined as the slope of the cost curve in region i at level l. The reduction in each of the segments is limited:

$$O \le R_{i,l} \le R_{i,l,max}\ for\ i=1,...,38\ s=1,..,.S \tag{23}$$

An identity relates emission reductions with unabated emissions (E_i) to calculate emissions remaining after abatement:

$$E_i = \overline{E}_i - \Sigma_s\ R_{i,s}\ \ for\ 1=1,...,38 \tag{24}$$

Total deposition (wet and dry) at each receptor j is calculated as the sum of the contributions of each source region plus the background deposition:

$$D_j = \Sigma_i\ a_{ij}\ E_i + b_j\ \ for\ j=1,...,J \tag{25}$$

with a_{ij} being the linear source-receptor relationship from region i to receptor j, as based on the atmospheric transport model. b_j is the background deposition which is not attributable to specific sources and considered as not reducible.

Furthermore, limits or targets can be set on the sulfur deposition for each receptor j (j=1,...,J):

$$D_j \leq D_j^* \tag{26}$$

Alternatively, so called policy constraints can be added on the maximum or minimum emissions remaining after abatement in each Region i to reflect e.g. abatement devices already in place:

$$E_i^{min} \leq \overline{E}_i - \Sigma_s R_{i,j} \leq E_i^{max} \tag{27}$$

The above equations form a large LP model that requires a significant amount of computer resources. Several algorithms have therefore been developed to speed computations, as well as allowing for rapid and interactive use of the model on a personal computer. First, each regional cost function is reduced to a maximum of eight segments. Region specific curves for SO_2 reduction may consist of up to 53 segments (Amann and Kornai, 1987). Smaller segments are merged in such a way that the deviation from the original curve remains below 2%. Secondly, the problem is reformulated so that initially emissions are fully abated so that emissions are reduced to the lowest technically feasible level. This implies that it is immediately known whether deposition targets are feasible. If targets are feasible, then emissions are increased in the LP program in order to maximize cost savings from the fully abated case. As a result many LP iterations are eliminated. Thirdly, results of previous optimization with similar characteristics are employed. Finally, filters are used to identify those receptors that may actually constrain the optimization. Other receptors, typically the majority, can be removed without affecting the solution.

If the objective is the attainment of a certain level of Europe-wide emissions the optimization problem is simpler:

$$Min\ C = \Sigma_i\ C'_{i,l} * R_{i,l} \tag{28}$$

subject to the condition:

$$\Sigma_i\ \overline{E}_i - \Sigma_i\ \Sigma\, R_{i,l} \leq \Sigma_i\ E_i^{max} \tag{29}$$

Again, the reductions in each of the segments l are limited to the technically feasible reductions. The solution to the problem is relatively easy. The segments of all the regional cost curves are ranked according to increasing marginal costs to form the so-called continental cost function. The associated emission reductions of each of the segments are added and subtracted from the unabated emissions. What remains are the total European-wide emissions after abatement. The cost minimum is easily determined since the point is sought where the emissions remaining after abatement equal the desired target.

5.3 The method to simulate bilateral trading

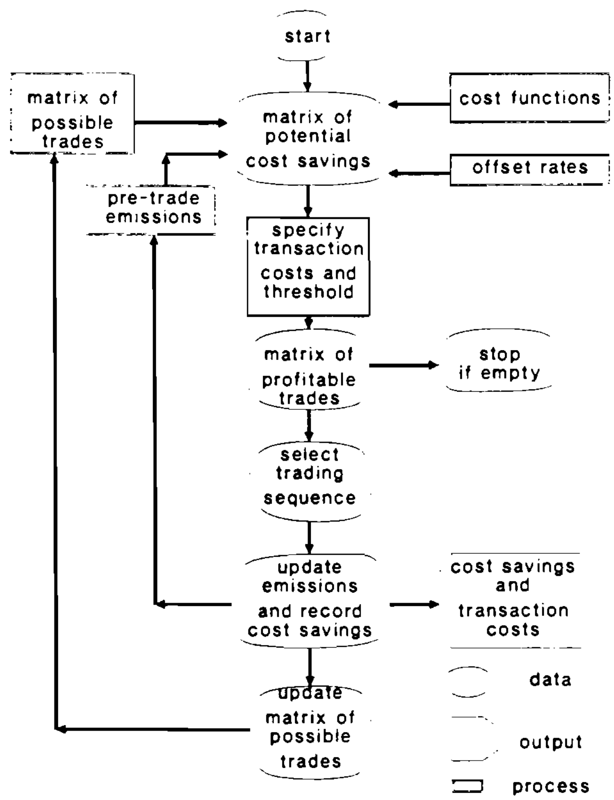
5.3.1 Introduction

Until recently, many model studies simply assumed that the potential cost savings of emission trading schemes would equal the results of optimization procedures; in other words, a perfectly working market where emission permits are simultaneously traded was assumed. Practice, as well as recent model studies (Atkinson and Tietenberg, 1991), show that in reality trading takes place bilaterally and sequentially. With such restrictions, trading is not expected to capture the complete cost savings possible according to any LP cost minimization procedure. The trading algorithm simulated here describes a process of repeated bilateral trading subject to an offset or exchange rate for every possible combination of bilateral trades. New elements are: the user can specify any offset rate including those that are unequal to one, the model allows for calculation of transaction costs and permits the setting of thresholds (based on perceived transaction costs) below which trades do not take place.

Figure 5 depicts a flow diagram of the trading algorithm. The diagram shows that the procedure consists of the following steps:

1. Creation of a matrix of potential cost savings from each potential bilateral trade.
2. Calculation of transaction costs and determination of threshold level, below which trades will not take place.
3. Selection of the trading sequence.
4. Updating of emissions after consummation of the selected trade and recording cost savings.
5. Updating of the matrix of possible trades, accounting for the trades that took place (return to step 1).

Figure 5. Flow diagram of bilateral trading



5.3.2 Creation of the cost saving matrix

As discussed above, cost functions estimated with the RAINS model are piece-wise linear. As a result, RAINS does not work by equalizing marginal costs but sorts and ranks elements of two (or more) cost functions according to their marginal costs (in ascending order). If a trade ratio is introduced, the determination of the cost-optimal bilateral combination of emission reductions can be performed in a similar way, taking into account the trade ratio. This implies the following modifications in the cost curves for the source y, the source decreasing emissions after trade:

1. The marginal costs of source y are multiplied with the exchange rate (reflects Condition 20).
2. The emissions of source y (after abatement) are divided by the exchange rate (reflects Condition 19). This consists of two elements:
   - dividing the unabated emissions,
   - dividing the volumes of emissions abated by each measure.
3. The segments of the cost functions of source x (the original one) are merged with the modified segments of source y and are ranked according to their (partly modified) marginal costs.
4. The pre-trade level of emissions of source y is divided by the exchange rate (Condition 20) in order to find the optimum emission levels with the exchange rate.
5. The point is determined where the (modified) emissions of this combined (modified) cost function (left hand side of Equation 19) are equal to the modified pre-trade emissions (right hand side of Equation 19). This is the cost-minimum solution for the bilateral trade.
6. The outcome of step 5 is compared with the costs of controlling emissions to the pre-trade emission levels using the original cost functions, and the cost savings are noted.
7. The procedure is repeated for every combination of bilateral trades until a matrix of cost savings of all possible trades is created.

5.3.3 Transaction costs

An evaluation of emission trading practices in the USA showed that transactions costs are frequently prohibitive to trading. In the literature, transactions costs are estimated at 10-30% of the costs savings (Dwyer, 1991). Building in transaction costs (Step 2 in Figure 5) thus gives a more realistic picture of the potential cost savings. The algorithm consists of the following steps:

1. Specify the level of transaction costs for each trade exogenously.
2. Specify a threshold level of (expected) transaction costs. If cost savings of a potential bilateral trade are below the threshold the trade is not profitable and will be skipped from further selection.

5.3.4 Selection of trades

After calculating the matrix of cost savings of all possible (and profitable) trades the sequence of trading is determined. Currently, the algorithm ranks all possible trades according to their cost savings and selects the one with the highest cost savings. Cost savings are defined as the difference between the total cost increase of the emission permit selling sources and the total cost decrease of the emission increasing source, between the pre-trade emission level (of every round) and the post-trade emission level. This is an optimistic assumption assuming perfect information and coordination of the selection of traders. An alternative (pessimistic) assumption, currently not implemented, would be that due to the imperfect information of traders, and due to the competition to get the trade accepted that is best for two individual trade partners and not necessarily the best in terms of highest overall cost savings, the selection of trade takes place at random.

5.3.5 Updating the emission matrix and the matrix of possible trades

Upon completion of the trade(s), the following steps are implemented:

1. Update the (pre-trade) emission vector, accounting for the trade(s) that took place.

2. Record the cost savings of the trade (compared to the pre-trade situation) in a file.

As a final step the matrix of possible trades is updated. Sources that have already traded are allowed to trade again, but not with the same partner: the cells of the cost-savings matrix corresponding to the trade between the two regions concluding the trade are skipped, and the cost savings of all the other trade relationships of these two countries are recalculated with the new emission levels.

5.4 Data on costs and atmospheric transport

The RAINS model contains a sub-module to assess the potential and costs for alternative emission abatement technologies. The evaluation is based on internationally reported performance and cost data of control devices (Amann and Kornai, 1987). Cost estimates for specific technologies are extrapolated by the model to reflect country-specific conditions such as operating hours, boiler size, and fuel price. In the current version of the model the cost evaluation of the emission reduction techniques is limited to the most relevant measures that have no impact on the underlying pattern of energy use. For the time being, energy conservation and fuel substitution are excluded from the analysis. The following technical options are implemented:

1. Use of low sulfur fuels and fuel desulfurization:
   This pertains to the use of fuels with a reduced sulfur content, such as fuels with a lower natural sulfur content or fuels that have undergone a desulfurization process. For low sulfur hard coal, the sulfur content is set at 1%. Desulfurization of gas oil and diesel oil can reduce the sulfur content in two steps: up to 0.3% and up to 0.15%. The desulfurization of heavy fuel oil is assumed to be possible up to a level of 1%.
2. Desulfurization of flue gases during or after combustion:
   This set of measures requires investments at the plant site. Three techniques are considered: desulfurization during combustion with removal efficiencies of 50% at relatively low costs, flue gas desulfurization with a removal efficiency of 95% at

moderate costs, and the use of advanced flue gas purification with emission reduction of 98% at high costs.

Not all abatement technologies are applicable for all fuel types and energy sectors (see Amann and Kornai, 1987). Moreover, a distinction is made between new and existing plants to account for the additional costs of retrofitting existing plants.

For the optimization mode RAINS creates 'national cost functions' for controlling emissions. National circumstances (such as sulfur content and operating hours) result in variations in the costs for applying the same technology in different countries in Europe. Another difference is the structural variations of energy systems, especially in the amount and structure of energy use, which determines the potential for application of individual control options. One way to combine these factors is to compile national cost functions. These functions display the lowest costs for achieving various emission levels by applying the cost optimal combination of abatement options. This is done by ranking the options according to their marginal costs and their individual potential for removal and can be performed within each fuel category. The cost curves used in this paper are based on official energy use projections for the year 2000 (Latest Energy Pathways) as published by the International Energy Agency (IEA, 1991).

Source-receptor transfer coefficients, which relate (country) emissions in the diffusion model to deposition at receptor points (for each grid), are based on the acid deposition model developed within the European Monitoring and Evaluation Program (EMEP) (Iversen et al., 1991). The model includes ten different chemical components in the air, three of which are man-made: SO_x, NO_x and NH_3. Input data for the model consist of emissions for the three pollutants and meteorological data such as precipitation, wind speed and temperature. Meteorological data are taken from a weather prediction model and direct observations. As far as possible emission data employed are official data submitted by the different countries. The model calculates transboundary fluxes of oxidized sulphur and nitrogen as well as reduced nitrogen (ammonia and its product ammonium). For the trade simulations presented in this paper, EMEP model results have been applied that reflect the meteorological average of the years 1985, 1987 to 1990.

6. RESULTS OF THE TRADE SIMULATION

6.1 Scenario setting

Current negotiations on the new sulfur Protocol focus on a set of sulfur deposition targets. Provisional (interim) deposition targets are available for ten countries. Because of the considerable emissions reductions implied by these proposed targets, recent discussion focused on the original target loads being increased uniformly by 10, 20, 30 or 40%. For the purpose of this study targets loads (as of December 1991), uniformly increased by 40%, have been selected as the reference targets (see Figure 6).

This section examines the cost-effectiveness, environmental impacts and distributive consequences of the following instruments (or scenarios) for achieving the target loads:

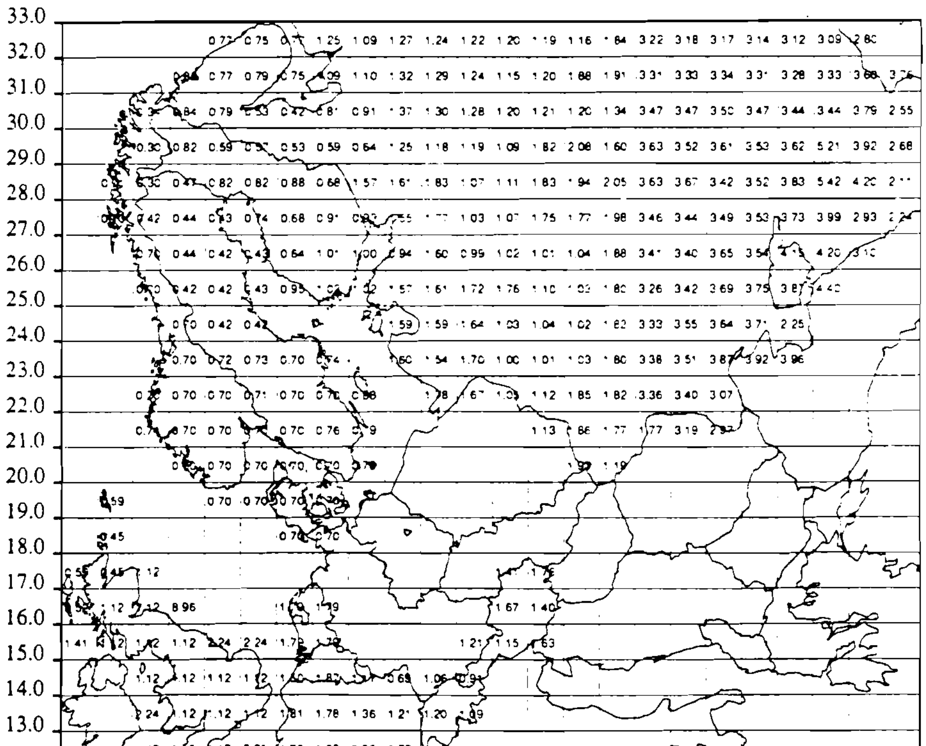
1. a cost-minimum allocation of measures (based on optimization);
2. a uniform percentage reduction for all countries;
3. emission trading with an offset rate of one; and
4. emission trading with an offset rate equal to the marginal costs in the optimum.

The allocation of reductions in Scenario 2 is steered by one 'binding' receptor in the United Kingdom. To meet the target load of this receptor, emissions have to be reduced by 84% in some countries. To create a 'flat-rate' scenario, this 84% reduction was applied to all other countries, where technically feasible. In those cases where such a reduction was not considered achievable by the measures implemented in the RAINS model, the maximum technically feasible reductions were assumed. Since the extent of emission reduction is mainly steered by the 'flat-rate' criterion, emission reductions in most countries are much higher than necessary to maintain target loads. Consequently, deposition is well below target loads at almost all receptor sites in Europe.

Both emission trading schemes (Scenarios 3 and 4) simulate bilateral, sequential trading. The trading scheme with an offset rate of one allows the exchange of emission reduction commitments on a one-to-one basis. Consequently, emissions are constant. The second scheme has a different ratio for each particular trade.

In principle, emission trading can start from any initial distribution of emission reduction commitments. In this example, both emission trading schemes start from the 84% emission reduction target of Scenario 2. This has the advantage that initially the target loads are not violated and, therefore, it allows to analyze whether or not emission trading results in violation of the targets. The trading simulation further assumes that emissions from sea regions (resulting from ships) are not allowed to be traded since there is no central authority who could act as a trading partner.

Figure 6. Target loads used in this paper (g $S/m^2/yr$)



6.2 Cost-effectiveness and environmental impacts of emission trading scenarios

Table 1 displays the major results of the various scenarios in terms of their emission control costs, the total remaining emissions, the overall exceedance of target loads and exceedance of the (5 percentile) critical loads. The Table shows that Scenario 1 (optimized allocation) is the most cost-effective means to achieve the target loads. Costs of uniform per cent reduction (Scenario 2) are twice as high as in Scenario 1. Starting from Scenario 2, both emission trading schemes result in cost savings over the uniform reduction. However, trading on a one-to-one basis (Scenario 3) reduces costs by 16% (10 milliard DM/year), whereas trading using the exchange rates (based on the ratios of the marginal costs, Scenario 4) leads to cost savings of 30% over the uniform cut-back (Scenario 2) but does not attain the cost minimum (Scenario 1). At the same time, environmental impacts are different for each scenario. Target loads are not violated, per definition, in Scenarios 1 and 2, and by keeping the very low initial level of emissions constant, one-to-one trading also does not result in exceeding target loads (at least in this particular case). The cost savings of Scenario 4 (exchange rate trading) are obtained by a substantial increase in emissions. Still this increase does not result in exceedance of target loads after trading due to the very low pre-trade level of emissions.

Table 1 also shows that emissions remaining after the uniform cut-back (Scenario 2) are much lower than in Scenario 1 (cost minimum). Due to the flat rate requirement, emissions also have to be reduced in places where it is not necessary to meet the deposition targets. Since Scenario 2 is taken as the starting point for trading, Scenario 3 (one-to-one trading) keeps the total European emissions constant at this level, but achieves cost savings by equalizing marginal costs for all emitters. Since the very low pre-trade emissions result in a strong overfulfillment of the target loads, the rearrangement of reduction measures introduced by emission trading does, in this case, not violate target loads.

The exchange rate trading (Scenario 4) results in a considerable increase in emissions, from 11760 kt to 19727 kt. Consequently, costs are much lower than with the uniform cut-back. In spite of this increase in emissions, target loads are not violated. Again, this is due to the fact that initial (pre-trade) emissions are very low. Consequently, deposition at all but one of the receptors is much lower than the target loads. Hence, if trading starts from this very low initial level, deposition at most receptors can be raised without exceeding the target loads.

Table 1: Comparison of scenario results

	SCENARIO			
	1	2	3	4
	COST-MINIMUM	UNIFORM % CUTBACK	EMISSION TRADING one-to-one	EMISSION TRADING exchange rate
Annual costs (Mio DM)	31200	63750	53267	44608
Annual costs (as % of uniform cutback)	49	100	84	70
Emissions (kt SO_2)	26524	11760	11760	19727
Exceedance of critical loads (% of land area)	23.0	10.4	10.1	12.6

Although target loads are not exceeded in any scenario, environmental impacts are different. Table 1 shows that a uniform cutback results in a smaller area (10%) being affected by deposition exceeding critical loads than in the optimized Scenario 1 (23%). This means that higher costs also result in higher environmental benefits, although marginal benefits decrease (costs are twice as high as in the cost minimum scenario but the area with deposition above critical loads only increases from 77% to 90%). Similar to Scenario 2, an exceedance of critical loads (10 % of land area) is also expected to result from one-to-one emission trading (Scenario 3), though at different locations and at lower costs. Trading subject to exchange rates (Scenario 4) leads to an exceedance of critical loads in 12.6% of the land area.

6.3 A closer look at the trading results

6.3.1 One-to-one trading (Scenario 3)

Under one-to-one trading, countries are allowed to trade their emission reduction commitments as long as total emissions remain constant. An increase in emissions by one country has to be offset by a decrease of the same amount in another country.

Table 2 shows the trades and sequence of trading that would result from one-to-one trading. Thirty trades are expected to be implemented, and the total cost saving of all trades amounts to 10.5 milliard DM/year. Nearly 90% of the cost saving is achieved by the first ten trades.

The first trade takes place between Turkey and FRG-E (former GDR). As Table 3 shows this is between the country with the highest marginal costs of the initial solution (Turkey) and one of the countries with the lowest marginal costs (FRG-E). Because of its high marginal costs Turkey buys permits and increases emissions by 254 kiloton SO_2. With an offset rate of one, FRG-E has to reduce emissions with the same amount. The total cost savings (decrease in pollution control costs of Turkey minus the additional costs for FRG-E) amount to nearly 2.4 milliard DM/year.

Table 3 shows that one-to-one trading tries to equalize marginal costs. Whereas marginal costs vary between 478574 and 849 DM/ton SO_2 before trading, the differences in marginal costs, after all trades are implemented, range between 4797 and 788 DM/ton SO_2.

Table 4 shows the remaining emissions and the pollution control costs (without transfer payments) that result after trading. The Table shows that the total amount of emissions is constant (11760 kilotons SO_2) before and after the trade. Although trading reduces total pollution control costs from 63.8 milliard DM/year to 53.3 milliard DM/year, the pollution control costs are still much higher than the cost minimum (31.2 milliard DM/year) of Scenario 1.

Table 2. Trades implemented with the one-to-one trading

Trade	Buyer	Amount ($kt\ SO_2$)	Remaining emission ($kt\ SO_2$)	Seller	Amount ($kt\ SO_2$)	Remaining emission ($kt\ SO_2$)	Offset rate	Cost savings (mio DM/y)
1	TUR	254	1595	GDR	-253	546	1.00	2389
2	POL	132	716	UKR	-131	939	1.00	1207
3	YUG	147	468	GDR	-146	400	1.00	1053
4	CZE	69	777	BYE	-69	100	1.00	911
5	BUL	38	275	BAL	-38	164	1.00	790
6	FRG	147	650	ITA	-146	467	1.00	785
7	ROM	43	357	UK	-43	730	1.00	687
8	SWE	70	165	TUR	-70	1525	1.00	496
9	KOL	143	254	RSU	-143	1008	1.00	456
10	HUN	27	607	ESP	-27	470	1.00	419
11	GRE	34	123	DEN	-34	37	1.00	347
12	AUS	15	78	GDR	-15	384	1.00	265
13	NOR	11	44	CZE	-11	766	1.00	136
14	ROM	136	493	FRA	-135	422	1.00	92
15	SWI	7	50	FRA	-7	415	1.00	91
16	IRE	8	58	FRA	-8	407	1.00	78
17	ALB	2	44	MOL	-2	77	1.00	68
18	LUX	5	7	NET	-5	68	1.00	63
19	UKR	57	996	ITA	-57	411	1.00	54
20	KOL	65	319	ITA	-65	346	1.00	35
21	BEL	6	137	FIN	-6	85	1.00	15
22	GRE	6	129	FIN	-6	79	1.00	12
23	POR	24	66	PET	-24	72	1.00	8
24	ESP	5	475	FRA	-5	402	1.00	7
25	AUS	1	79	NOR	-1	43	1.00	6
26	TUR	9	1534	FIN	-9	70	1.00	4
27	TUR	16	1550	ITA	-16	330	1.00	3
28	TUR	2	1553	BUL	-2	272	1.00	2
29	PET	2	73	NOR	-2	42	1.00	2
30	ESP	1	475	PET	-1	73	1.00	1

Table 3. Marginal costs of one-to-one trading (DM/ton SO_2)

Country	Pre-trade	Post-trade	Optimum
ALB	52303	4468	0
AUS	260858[1)]	3579	2469
BEL	7280	3203	3203
BUL	58711[1)]	3981	0
CZE	177001[1)]	2874	921
DEN	2725	2725	2725
FIN	4498	4498	2832
FRA	4321	4321	9506
FRG-W	9283	2392	9278
FRG-E	849	3347	3347
GRE	90828[1)]	3230	0
HUN	186770[1)]	4231	4231
IRE	65772[1)]	2401	0
ITA	2315	4719	2315
LUX	19511	3063	9327
NET	3584	3584	3109
NOR	101111[1)]	3753	0
POL	584199[1)]	2095	2095
POR	5137	2136	0
ROM	201891[1)]	839	839
SPA	1333	1333	249
SWE	61302[1)]	2156	1240
SWI	112496[1)]	4316	7987
TUR	478574[1)]	3048	0
UK	1573	1573	1573
YUG	155638[1)]	1621	1621
KOL	52376[1)]	2056	2056
PET	4797	4797	831
BAL	900	900	5492
BEY	811	2142	811
UKR	993	993	993
MOL	788	788	788
RSU	4063	4063	492

1) Maximum feasible reduction

Table 4. Emissions and costs after one-to-one trading

Country	Emissions (kt SO_2)			Costs (million DM/year)		
	Initial	Post-trade	Optimal	Initial	Post-trade	Optimal
ALB	41	43	168	236	165	0
AUS	62	78	232	976	651	188
BEL	131	136	136	954	914	914
BUL	236	272	1556	2410	1595	0
CZE	708	766	966	2961	1966	1390
DEN	71	37	52	374	467	426
FIN	91	70	278	983	1077	232
FRA	558	402	402	1752	2425	2420
FRG	503	649	612	5576	4215	4560
GDR	800	384	546	1352	2109	1568
GRE	88	128	920	1401	922	0
HUN	580	607	608	1114	635	636
IRE	50	57	234	392	281	0
ITA	614	330	818	2868	4090	2400
LUX	2	7	5	95	12	28
NET	73	67	234	660	679	92
NOR	33	41	125	324	166	0
POL	584	716	1624	5915	4312	2420
POR	42	66	364	615	490	0
ROM	313	493	494	3712	2277	2280
ESP	497	475	2280	2198	2227	354
SWE	94	164	328	1189	427	97
SWI	43	50	50	207	84	84
TUR	1341	1552	3260	5008	2535	0
UK	773	729	748	4006	4075	4040
YUG	321	468	1508	4468	2924	1236
BAS	29	29	29	53	53	53
NOS	69	69	69	125	125	125
ATL	126	126	316	228	228	0
KOL	111	319	340	1877	498	456
PET	96	71	286	404	519	88
BAL	202	164	164	664	698	698
BYE	169	100	476	410	526	162
UKR	1071	995	996	2999	3074	3080
MOL	79	77	77	290	291	292
RSU	1151	1007	5220	4938	5520	878
SUM	11760	11760	26524	63750	53267	31200

6.3.2 Exchange rate trading (Scenario 4)

Whereas in Scenario 3 a uniform offset rate of one was selected, this example explores the scope for non-uniform offset rates. Since offset rates are instruments to determine the profitability and thereby the economic potential for individual trades, a selection of appropriate rates could steer the trading process into certain desired directions.

As outlined in the introductory section of this paper there are doubts about the practical applicability of optimization approaches to allocate international emission reduction requirements. It has been argued that, as an alternative, properly designed emission trading schemes could possibly achieve the cost optimal solution without centralized information on emission control costs.

To steer the trading process into this direction, one of the Kuhn-Tucker conditions for the cost minimum (Equation 9 in Section 2) is used to determine the offset rate of emission trading between two countries. Thereby, the offset rate (Wxy) is set equal to the ratio of the marginal costs of emission reductions in the optimum (MCi):

$$Wxy = MC1/MC2$$

For example, marginal costs of country i of 2000 DM/t SO_2 and of country j of 1000 DM/t SO_2 result in an offset rate of 2:

$$\frac{MC_1}{MC_2} = \frac{2000}{1000} = \frac{2}{1} = 2$$

This implies that if source 1 increases emissions with one unit, source 2 can reduce its emissions with 2 units. Since marginal costs in the optimum generally differ among countries, the offset rates for the bilateral trades will also be different for each trade combination.

Costs of emission reductions can be described in several ways. Whereas some theoretical economic analyses assume continuous cost curves, other more technologically oriented approaches use piecewise linear cost curves. It is, however, in the nature of linear optimization that the optimal status of most variables of an optimization problem will lie exactly at the corner points of the solution space, i.e. on the intersections of the linear cost function segments. For these points, however, a unique definition of marginal costs does not exist.

The marginal costs for increasing emission reductions are different to the marginal costs for decreasing emission reductions. Since the proposed rule for deriving offset rates is not well defined for these situations, this simulation uses the higher marginal costs (i.e. the additional costs of further reducing emissions (represented by the next step of the cost curve) by default. This assumption also avoids problems occurring with marginal costs of zero, for which the definition of the offset rate according to Equation 9 is not applicable (MCj = 0).

Table 5 shows the trades that are expected to be implemented for this scenario. The offset rate differs among the implemented trades between 0.03 (Trade 6) and 11.12 (Trade 21).

The first trade takes place between Turkey and France. Due to Turkey's rapid economic development, the marginal costs of the pre-trade initial status, i.e. the 84% emission reduction (compared to 1980), are extremely high. The optimal solution, however, does not prescribe any emission reductions for Turkey since Turkey's emissions do not deposit on those areas for which target loads have been specified. Consequently, the marginal costs of the optimal solution are very low. The resulting exchange rate with France of 0.08 (i.e. French marginal costs of the optimum are only 8% of the marginal costs in Turkey) allows Turkey to increase its emissions by 1912 kt up to the unabated level (i.e. 3254 kt of SO_2), whereas France would reduce its emissions by 1912 * 0.075 = 144 kt. This saves Turkey abatement costs of 5.0 milliard DM/yr, while costs in France increase with 622 million DM/yr. The net cost savings of this trade are 4.4 milliard DM/yr.

Table 5. Trades implemented with exchange rate trading

Trade	Buyer	Traded Amount ($kt SO_2$)	Remain. Emission ($kt SO_2$)	Seller	Traded Amount ($kt SO_2$)	Remain. Emission ($kt SO_2$)	Offset Rate	Cost Saving (mio DM/yr)
1	TUR	1912	3254	FRA	-144	414	.08	4386
2	RSU	2827	3978	GDR	-414	384	.15	2437
3	BUL	1303	1540	FRA	-93	321	.07	1579
4	POL	166	750	BAL	-64	138	.38	1499
5	ESP	2568	3065	FRA	-67	254	.03	1401
6	YUG	709	1030	FRG	-124	379	.17	1306
7	ROM	1087	1401	YUG	-560	468	.52	1285
8	KOL	350	461	ROM	-856	544	2.45	951
9	CZE	58	766	KOL	-81	380	1.40	829
10	SWE	210	304	TUR	-362	2891	1.73	778
11	GRE	249	338	ESP	-792	2272	3.18	641
12	HUN	30	610	KOL	-61	319	2.06	365
13	AUS	45	108	ITA	-48	566	1.07	318
14	POR	274	316	BUL	-350	1188	1.28	280
15	NOR	79	112	UK	-43	730	.55	245
16	IRE	107	157	DEN	-34	37	.32	213
17	PET	86	182	POL	-34	716	.40	158
18	ALB	103	145	UKR	-75	996	.73	142
19	FIN	132	223	TUR	-520	2370	3.96	118
20	SWI	2	45	BYE	-23	146	9.84	63
21	LUX	5	7	ROM	-50	493	11.12	35
22	RSU	227	4205	GRE	-140	197	.62	25
23	BEL	6	137	BUL	-26	1162	4.74	18
24	RSU	186	4391	TUR	-128	2242	.69	18
25	RSU	147	4538	POR	-84	233	.57	12
26	RSU	111	4649	ALB	-76	69	.68	11
27	RSU	29	4678	SWI	-2	44	.06	7
28	RSU	22	4700	HUN	-3	607	.12	5
29	RSU	32	4733	NET	-5	68	.16	5
30	RSU	21	4754	LUX	-1	5	.05	5
31	RSU	15	4769	NOR	-9	103	.57	4
32	RSU	67	4836	IRE	-38	120	.57	1
33	RSU	146	4981	AUS	-29	79	.20	1
34	RSU	7	4988	BUL	-5	1157	.73	1
35	RSU	3	4991	MOL	-2	77	.62	1

After consummating the first trade, pre-trade emissions change and the potential cost savings of all remaining bilateral trades with either France or Turkey involved are calculated again. The trade with the highest cost saving is implemented. This procedure is repeated until no trade with cost savings above a certain threshold (in the example 0.1 million DM/year) is left.

Table 5 shows that 35 trades will be implemented under the exchange rate regime. The total cost savings per year would amount to 19.0 milliard DM/year. The gains from the first ten trades add up to nearly 90% of the total cost savings. As can be seen, a number of countries (e.g. Turkey, France, Remaining part of the former USSR, Poland, Kola Peninsula) would trade with several partners.

The extent to which exchange rate trading is able to approach the cost-minimum solution can be seen from combining Table 6 and Table 7. Table 6 indicates that 22 countries (out of 33) have marginal costs that are equal to the marginal costs in the optimum. This implies that trades between these 22 countries does not result in cost savings since their marginal cost ratio equals the exchange rate. The results further suggest that of the other trades still possible the cost savings are smaller than the threshold of 0.1 million DM/year.

Although 22 countries have marginal costs equal to the optimum marginal costs, only six countries (Belgium, Hungary, Luxembourg, Rumania, Ukraine and Moldavia) actually reach the same emission levels, i.e. they end up in a different part of the same segment of the cost curve. An example is France where the optimum (402 kt SO_2) is the upper end, and the pre-trade emissions (253 kt SO_2) is the lower end of the same segment (of 9506 DM/ton SO_2) of the cost curve.

Table 6. Marginal costs of exchange rate trading (DM/ton SO_2)

Country	Pre-trade		Post-trade		Optimum	
ALB	52303		1989		(725)	2)
AUS	260858	1)	3579		2469	
BEL	7280		3203	*	3203	
BUL	58711	1)	842		(676)	2)
CZE	177001	1)	2874		921	
DEN	2725		2725	*	2725	
FIN	4498		2832	*	2832	
FRA	4321		9506	*	9506	
FRG-W	9283		9283	*	9283	
FRG-E	849		3347	*	3347	
GRE	90828	1)	988		(794)	2)
HUN	186770	1)	4231	*	4231	
IRE	65772	1)	1231		(865)	2)
ITA	2315		2315	*	2315	
LUX	19511		9327	*	9327	
NET	3584		3584		3109	
NOR	101111	1)	869	*	(869)	2)
POL	584199	1)	2095	*	2095	
POR	5137		1130		(1130)	2)
ROM	201891	1)	839	*	839	
SPA	1333		249	*	249	
SWE	61302	1)	1240	*	1240	
SWI	112496	1)	7987	*	7987	
TUR	478574	1)	911		(716)	2)
UK	1573		1573	*	1573	
YUG	155638	1)	1621	*	1621	
KOL	52376		2056	*	2056	
PET	4797		831	*	831	
BAL	900		5447	*	5447	
BEY	811		811	*	811	
UKR	993		993	*	993	
MOL	788		788	*	788	
RSU	4063		722		492	

1) Maximum feasible reduction
2) Figure in brackets gives the marginal costs used to calculate the exchange rate/offset rate
* Marginal costs after trade equal the optimum marginal costs

Table 7 also shows that emissions will increase after trading from 11760 to 19727 kt. The emissions are still lower than necessary (26654 kt SO_2) to meet the cost minimum. As a result pollution control costs, although below the initial level of 63.7 milliard DM/year, are (with 44.6 milliard DM/year) still above the cost minimum.

Several reasons are responsible for the non-attainment of the optimal solution:

- The offset rate is based only on one condition for the optimum solution. Others, which have influence on the optimum status, are ignored.

- The concept of marginal costs is not well defined and ambiguous for piecewise linear cost curves. In the optimum solution the stepwise cost function allows for two optimal marginal costs. The exchange rate, however, is only based on one of them.

- Not all emitters are included in the trading scheme. As mentioned before, emissions from sea transport are excluded from trading because of the lack of trading agents. Although this reason is of minor importance in this example, non-participation of some countries (for any reasons whatsoever) might disturb the whole system considerably.

Table 7. Emissions and costs after exchange-rate trading

Country	Emissions (kt SO_2)				Costs (million DM/year)		
	Initial	Post-trade		Optimal	Initial	Post-trade	Optimal
ALB	41	69		168	236	89	0
AUS	62	78		232	976	651	188
BEL	131	136	•	136	954	914	914
BUL	236	1157		1556	2410	332	0
CZE	708	766		966	2961	1966	1390
DEN	71	37		52	374	467	426
FIN	91	222		278	983	391	232
FRA	558	253		402	1752	3836	2420
FRG	503	379		612	5576	6725	4560
GDR	800	384		546	1352	2109	1568
GRE	88	197		920	1401	701	0
HUN	580	607	•	608	1114	635	636
IRE	50	119		234	392	133	0
ITA	614	565		818	2868	2979	2400
LUX	2	5	•	5	95	28	28
NET	73	67		234	660	679	92
NOR	33	103		125	324	18	0
POL	584	716		1624	5915	4312	2420
POR	42	232		364	615	134	0
ROM	313	493	•	494	3712	2277	2280
ESP	497	2272		2280	2198	353	354
SWE	94	304		328	1189	125	97
SWI	43	43		50	207	139	84
TUR	1341	2241		3260	5008	876	0
UK	773	729		748	4006	4075	4040
YUG	321	468		1508	4468	2924	1236
BAS	29	29	•	29	53	53	53
NOS	69	69	•	69	125	125	125
ATL	126	126	•	316	228	228	0
KOL	111	319		340	1877	498	456
PET	96	181		286	404	175	88
BAL	202	138		164	664	839	698
BYE	169	145		476	410	429	162
UKR	1071	995	•	996	2999	3074	3080
MOL	79	77	•	77	290	291	292
RSU	1151	4990		5220	4938	1012	878
SUM	11760	19727		26524	63750	44608	31200

• (optimum)

6.4 The sensitivity of the trade simulations

6.4.1 Introduction

The results discussed above depend on the specific situation assumed for these scenarios and they may be sensitive to changes in:

- pre-trade emission levels,
- transaction costs,
- availability of information to the traders (perfect or imperfect) on the potential cost savings of each trade,
- information on cost functions available to the environmental agency determining the exchange rate or offset-rates,
- assumptions made on the behavior of the trading partners.

6.4.2 Changes in pre-trade emissions and transaction costs

Table 8 explores the sensitivities introduced by the first two items by analyzing a different starting point (i.e. starting from the optimum solution instead of the uniform 84% reduction), and by including transaction costs on the performance of emission trading with an exchange rate. It can be seen (compare with Table 1, cost minimum) that if exchange-rate trading started from the optimum it would stay close to the optimum. Two trades take place that only marginally change emissions. The first trade allows Turkey to reduce emissions and the Baltic region to increase. These trades are caused by the definition problem of marginal costs in the optimum mentioned before. The traded amounts, however, are limited. As a result cost savings are very small and the target loads are not exceeded.

Table 8. Sensitivity of exchange rate trading

SCENARIO: RESULTS:	EMISSION TRADING exchange rate	PRE-TRADE EMISSIONS of optimum	TRANSACTION COSTS 50 mio DM/trade per year
Annual costs (Mio DM)	44608	31195	44750
Annual costs (as % of cost minimum)	143	100	143
Emissions (kt SO_2)	19727	26537	19343

The second example analyzes the potential influence of non-zero transaction costs (costs of finding a trading partner, agreeing upon a trade, getting a trade accepted). An assumed level of 50 million DM/year per trade would reduce the number of profitable trades to 19 (instead of 35). The pollution control costs would not differ significantly from the reference scenario, but the distribution of emissions would change considerably (a number of trades would not take place). Still, the target loads are not violated. This is due to the fact that initial emissions are very low, oversatisfying targets at most receptors. It can be concluded that in this case the impact of transaction costs on cost savings is negligible.

An item for further analysis is the extent to which target loads are exceeded if one starts from higher initial emissions than the 84% flat rate reduction. In this case initial depositions are closer to their target, increasing the chance of exceedance.

Although exchange rate trading does not result in exceedance of target loads, at least not in the examples shown, simple one-to-one trading does if one starts from the optimum emission level (see Table 9). Although overall European emissions are kept at the same level as before, their geographical distribution differs, resulting now in exceedance of target loads in 2% to 95% of the land area of those countries that submitted target loads. Since one-to-one trading moves towards equal marginal costs, pollution control costs are reduced (only

73% of initial solution). However, this cost decline is not a real saving because environmental impacts are different.

Including transaction costs again does not influence results significantly. Annual costs are slightly higher than in the reference case. As before, the distribution of emissions differs from the reference case, and the fact that (the low initial) level of emissions is constant prevents violation of target loads.

Table 9. Sensitivity of one-to-one trading

SCENARIO: / RESULTS:	EMISSION TRADING one-to-one	PRE-TRADE EMISSIONS of optimum	TRANSACTION COSTS 50 mio DM/trade per year
Annual costs (Mio DM)	53267	22698	53363
Annual costs (as % of cost minimum)	171	73	171
Emissions (kt SO_2)	11760	26524	11760
Exceedance of target loads (% of land areas)	0	1.6 - 95	0

6.4.3 Other assumptions

Three other assumptions deserve qualitative discussion. First, the algorithm assumes perfect information: trades are implemented in descending order of their cost-savings. Assuming imperfect information (random trading) would probably result in considerably lower cost savings than in the first case (see Atkinson and Tietenberg, 1991). This requires further analysis.

Second, to set the exchange rate it is assumed that the environmental agency has perfect information about abatement costs when determining the optimal solution. It appears more realistic however to assume that this information is less than perfect, not least because cost functions depend crucially on the underlying prediction of future energy consumption.

Although the energy scenario used is based on the latest available information and has been partly reviewed by parties to the UN/ECE convention, considerable uncertainty on Europe's energy future still remains.

Consequently, if the agency sets exchange rates on centrally perceived cost curves it might well be that countries trade on the basis of what they individually see as realistic cost functions. The results of emission trading will therefore differ from the expectations of the agency. As a result, the emission pattern determining environmental impacts will also be uncertain. One should, however, realize that this uncertainty on environmental impacts is connected to every strategy that is unable to fix total emission ceilings in each European country.

Third, given initial emission and exchange rates, it is assumed that trading partners will try to minimize costs. Although this is a realistic assumption for firms operating on a competitive market, it is doubtful whether this is an adequate assumption for the behavior of countries in an international context (Kremeniouk, 1991). Countries might well place more emphasis on their environmental targets than on cost-effectiveness. Moreover, aspects of administrative practicality as well as political considerations are likely to play an important role (compare Opschoor and Vos, 1989).

6.5 Distribution of costs after emission trading

Not only are the overall European environmental impacts relevant, but also their regional distribution. One of the favorable aspects of emission trading is that it allows for a redistribution of costs such that every country is better off in the sense of having lower costs. In this context costs consist of pollution control costs plus transfers made between countries that agree on a trade. If a trade takes place, one country will have higher abatement costs (the seller of permits), the other will have lower costs. However, if a trade is profitable, the sum of the pollution control costs will be lower.

Table 10 displays the impacts on costs at a country level. In calculating the cost distribution after trading, we assumed that the countries with reduced control costs will compensate for the higher pollution control costs of their trading partner (the permit seller). Moreover, in this table a 50/50 division of the net cost-savings is assumed. Table 10 shows that compared to a uniform percentage reduction, all countries face lower costs under both trading schemes.

Remarkably, some countries will have negative net costs: their pollution control costs are lower than the sum of the transfers they receive from the cost savings in other countries. This is the case for France and the Baltic region in exchange rate trading, and for FRG-E and Byelorussia in one-to-one trading. This effect is caused by the initial distribution: the uniform scenario asked for a 84% reduction. As a result, some countries had to carry out their maximum feasible reductions and hence were unable to decrease emissions further to become permit sellers. Other countries (e.g. France) can decrease emissions beyond the 84% level and were thus able to further reduce costs by selling permits.

It is important to mention that the final distribution of costs after trading can be influenced by allocating more permits to economically less developed countries, which can then sell permits to reduce costs. In doing so, one has to take care that deposition targets are not violated. The fact that for every country costs are lower, or at least equal, after trading is however a typical, attractive feature of emission trading.

6.6 Distribution of environmental benefits

The regional environmental impacts of emission trading are not immediately clear-cut but depend on specific circumstances. One may expect, however, that the chance is higher that target loads, initially met, will be exceeded using the exchange rate than with the one-to-one case for two reasons:

- Emission trading subject to exchange rates may increase overall emissions.
- Emissions are redistributed to a greater extent, so that the final distribution differs much more than the pre-trade distribution.

Starting from extremely low initial emission levels, neither the one-to-one trading nor the exchange rate trading violate the target loads in any country. On the one hand, this is due to the fact that initial emissions are very low and, on the other, to the fact that the offset rates are based on the transfer coefficients of the receptors that are binding in the optimum. Hence, to a certain degree the exchange rate takes care of the impact of location on deposition.

Table 11 shows that some countries will experience a higher exceedance of critical loads as a result of trading than they would with uniform reduction, whereas others will be lower. One-to-one trading results in more negative environmental impacts for Austria, CSFR, West-Germany, and Hungary. The results for Albania, Belgium, Bulgaria, Finland, France, Ireland, Luxembourg, Netherlands, Portugal, Romania, Spain, Sweden, Turkey, United Kingdom, Yugoslavia and the USSR are indifferent. Other countries gain environmental benefits from trading.

With exchange rate trading, in some countries (Bulgaria, CSFR, France, FRG-W and FRG-E, Poland, Sweden and Yugoslavia) the exceedance of critical loads is smaller than with uniform reduction. In other countries (Belgium, Finland, Greece, Hungary, Norway and the remaining part of the former USSR) a larger area experiences an exceedance of critical loads. For all other countries there is no difference.

It has to be stressed again that in the example presented in this paper, the original target loads as submitted by ten countries, were increased by 40% in order to open space for emission trading. This reduces the direct relationship between target loads and critical loads.

Table 10. Distribution of annual costs (million DM/yr)

SCENARIO: COUNTRY:	COST-MINIMUM	UNIFORM % CUTBACK	EMISSION TRADING one-to-one	EMISSION TRADING exchange rate
Albania	0	236	202	159
Austria	188	976	841	817
Belgium	914	955	948	949
Bulgaria	0	2410	2014	1471
CSFR	1390	2962	2430	2547
Denmark	426	375	202	268
Finland	232	984	969	925
France	2420	1753	1619	-1930
Germany, West	4560	5576	5184	4923
Germany, East	1568	1353	-501	134
Greece	0	1402	1223	1068
Hungary	636	1115	906	930
Ireland	0	393	354	286
Italy	2400	2868	2430	2709
Luxembourg	29	96	65	78
Netherlands	92	661	630	659
Norway	0	325	253	200
Poland	2420	5915	5312	5086
Portugal	0	616	612	470
Romania	2280	3713	3324	2576
Spain	354	2198	1985	1178
Sweden	97	1190	942	801
Switzerland	85	208	163	173
Turkey	0	5008	3561	2358
UK	4040	4007	3664	3884
Yugoslavia	1236	4468	3942	4468
Kola-Karelia	456	1877	1632	1517
S.Petersburg	88	404	399	325
Baltic region	698	664	269	-86
Byelorussia	162	411	-45	379
Ukraine	3080	3000	2370	2929
Moldavia	292	291	257	291
Rem.Eur.USSR	878	4938	4710	3671

Table 11. Exceedance of critical loads[1)] (% of land area)

SCENARIO: COUNTRY:	COST-MINIMUM	UNIFORM % CUTBACK	EMISSION TRADING one-to-one	EMISSION TRADING exchange rate
Albania	0	0	0	0
Austria	100	9	14	9
Belgium	27	27	27	20
Bulgaria	53	0	0	24
CSFR	81	64	69	66
Denmark	30	25	20	25
Finland	24	10	10	23
France	2	2	2	0
Germany, West	82	65	72	31
Germany, East	67	49	35	35
Greece	4	0	0	4
Hungary	32	9	23	23
Ireland	42	6	6	6
Italy	16	3	0	3
Luxembourg	0	0	0	0
Netherlands	95	95	95	95
Norway	63	38	36	47
Poland	70	40	31	31
Portugal	14	0	0	0
Romania	10	0	0	0
Spain	0	0	0	0
Sweden	76	51	50	67
Switzerland	30	22	0	22
Turkey	1	0	0	0
UK	26	26	26	26
Yugoslavia	20	0	0	5
USSR regions	12	1	1	2

1) Exceedances are expressed in terms of 5 percentile critical loads, except for countries where this percentile results in zero values. In those cases the 50% values were used.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

In general, emission trading systems may offer an alternative approach in achieving cost-effective implementation of effect-oriented policy targets. Whereas several trading options have been proposed to deal with uniformly dispersed pollutants (such as CO_2), the situation is much more complex when considering non-uniformly dispersed pollutants where the location of the emission source is of importance (e.g. for SO_2), if certain regional exposure levels should be maintained.

Cost-effectiveness implies that a certain environmental objective is achieved at minimum cost. If the objective is the attainment of a fixed level of emissions, cost-effectiveness requires that marginal costs per ton emission controlled are equalized. If the objective is a set of deposition targets, the marginal costs per ton emission abated will generally have to be different since they have to reflect the transfer of emission from the sources to the receptor areas.

In theory, trading deposition (or ambient) permits would fulfill the conditions for cost-minimal resource allocation. In such a case, a separate market has to be established for every receptor area and the polluters have to act on a large number of markets simultaneously. The system is expected to be too complex for practical implementation.

A number of alternative simpler trading schemes have been suggested and partly applied in practice: emission trading in one zone, in several zones, trading of deposition permits for only one (critical) receptor and trading subject to trading rules with respect to the deposition. The first three systems do not guarantee that the deposition targets are met or they result in excessive costs. Trading subject to trading rules requires the use of a dispersion model to analyze deposition levels before and after each single trade. Although this is a guarantee for avoiding "hot spots", the system is complex for the traders and is likely to reduce potential cost savings in practice.

One relatively simple system is to allow sources to trade according to a fixed offset rate. The offset rate defines the amount of emissions one source has to decrease if another source increases emissions with one unit. From a number of formal conditions for the cost-minimum solution, the ratios of the marginal costs of abatement in the optimal solution are introduced into a new trading scheme as offset or exchange rates for emission trades. Thereby the transfer coefficients of those receptors that are binding in the optimum are taken into account. It is shown that, generally, because other necessary conditions for an optimum solution are neglected, this system will not achieve the optimal solution. In addition, such a trading system does not guarantee that environmental deposition constraints are not violated. There is also no indication that such a system would move towards the 'real' optimum in case of imperfect or incorrect centralized information on abatement costs since in this case the ex-ante set exchange rates are incorrect.

Since the results of both emission trading and optimization are sensitive to regional circumstances, there might be a chance that proper trading rules could improve the cost-effectiveness of an initial (non-optimal) allocation and move towards the optimum. Based on the IIASA RAINS model a routine has been developed to simulate bilateral, sequential emission trading for the specific situation of reduction of SO_2 emissions in Europe.

For a set of arbitrary target loads, calculations identified the cost-minimal allocations of emission reductions and the required uniform reduction strategy to satisfy the selected target loads. Taking an 84% uniform reduction strategy as a starting point, emission trading simulations achieved cost savings. A one-to-one offset rate (keeping total European emissions constant), limits the potential cost savings to 16%; deposition targets are not violated since initial emissions allocation overfulfilled targets at many places. If an exchange rate, based on marginal costs, is applied to trading, total emissions increase considerably thereby achieving more significant cost savings (30%). Again, due to the low level of pre-trade emissions, the specified target loads are not exceeded in this particular case.

The results of emission trading are sensitive to a number of assumptions, such as the pre-trade emission levels, the transaction costs, the availability of information on potential cost savings and assumptions made on the behavior of trading partners.

If emission trading would start from the optimum, one-to-one trading would result in exceedance of target loads. Exchange rate trading based on the marginal costs in the optimum would hardly take place since in this specific case cost savings are not possible. Hence target loads are not violated. The introduction of transaction costs has no significant impact on the results. Apart from the pre-trade emission levels, results do however depend on the following assumptions:

- the environmental agency has perfect information on pollution control costs necessary to determine the exchange rate,
- the sequence of the trade assumes that trades with the highest cost savings are implemented first,
- countries are assumed to minimize their pollution control costs and agree to share the cost savings.

7.2 Recommendations

This paper introduced a first attempt to analyze and simulate alternative schemes of trading emission permits in Europe. Many aspects have been addressed only briefly and deserve more analysis before comprehensive conclusions on the potential role of emission trading systems can be drawn. The following tasks should be analyzed in more detail:

- simulation of emission trading starting from other pre-trade emissions, especially for emission levels closer to the optimum,
- cases in which the agency has imperfect information on the cost functions (exchange rates are based on different costs than the traders use),
- alternative assumptions on the sequence of trading: random instead of selecting the trades with the highest cost savings first.

In order to guarantee that target loads are not violated after any trade, it is also recommended to analyze how results are influenced if, after each single trade, a diffusion model is run to test the exceedance of target loads. In that case only those trades would be allowed that do not result in violation of the deposition standards.

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