OPTIONS AND COSTS OF CONTROLLING AMMONIA EMISSIONS IN EUROPE

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Preface

Ammonia emissions make a significant contribution to the European acidification problem. Consequently, strategies to reduce acidification should consider not only measures to abate emissions of sulfur dioxide and nitrogen oxides, but should also include the potential for and the costs of reducing ammonia emissions.

This paper presents some research results obtained by IIASA's project on Transboundary Air Pollution. For the first time a consistent analysis explored the available options and the costs for reducing ammonia emissions for all European countries. Results of this study have been incorporated into the "Regional Air Pollution Information and Simulation" (RAINS) model, which provides an integrated assessment tool for the acid rain problem in Europe.

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Options and costs of controlling ammonia emissions in Europe*

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Summary

Ammonia emissions contribute to acidification in Europe. The major emission sources are livestock and fertiliser use. This study presents the costs of controlling ammonia emissions in 33 regions in Europe. Abatement options include low nitrogen feed, stable adaptations, covering manure storage, cleaning stable air, and low ammonia applications of manure. Cost estimates are based on country- and technology-specific data. Variations in average costs, and the structure of livestock population and fertiliser use, cause considerable differences in costs between countries for applying similar reductions or techniques. Allowing countries to choose their own mix of control options would be more cost-effective.

Keywords: Costs; air pollution; livestock; ammonia; fertiliser.

1. Introduction

Although public concern with the detrimental impacts of acidification in Europe initially centred on sulphur, it is now accepted that nitrogen is also an important factor. Nitrogen deposition results both from emissions of nitrogen oxides (NO_x) and ammonia (NH_3). Whereas the major sources for nitrogen oxides are traffic, power plants and industry, livestock farming and the use of artificial nitrogen fertiliser are the most relevant sources of

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ammonia emissions (Asman, 1992; Klaassen, 1991b). Ammonia has direct and indirect impacts on the enviroment. Indirect impacts occur through the saturation of soils with nutrients and the acidification of lakes and forest soils (Asman, 1987; Roelofs and Houdijk, 1991). Direct impacts on vegetation may occur with high concentrations in the vicinity of the source. Indirect impacts, however, also occur on an international level since ammonia emissions are transported in the air over long distances. Evidence suggests that current levels of nitrogen deposition exceed those below which no significant harmful effects to sensitive ecosystems occur (Hettelingh et al., 1991). The contribution of ammonia to total potential acidification in Europe was around 25 per cent in 1989. Its contribution to total nitrogen deposition in the same year was around 50 per cent.

The Regional Acidification Information and Simulation (RAINS) model, developed at the International Institute for Applied Systems Analysis (IIASA), combines information on several stages of acidification in Europe: the sources of emissions and the potential for their abatement, the atmospheric transport and the environmental effects of acid deposition (Alcamo et al., 1990). The United Nations Economic Commission for Europe uses RAINS in their negotiations on a new protocol to reduce sulphur emissions in Europe. Future negotiations are expected to focus on total acidification, including ammonia. The analysis of the potential and costs of control strategies form an essential part of the RAINS model. Costs for controlling sulphur, as well as nitrogen oxides emissions, are already incorporated in the model; its potential and costs for controlling NH_3 emissions, however, has not yet been incorporated.

The objective of this study is to describe and discuss the method and data used to evaluate the possibilities and costs of controlling ammonia emissions in 33 countries in Europe.

The requirement to assess the abatement costs for all countries in Europe necessarily limits the level of detail that can be maintained: regional disaggregation is determined by the availability of atmospheric transport matrices. Currently, matrices are available that calculate the ammonia deposition in around 550 land-based grids (of 150×150 km) resulting from emissions from 33 countries in Europe, including 7 regions in the former USSR (Sandnes and Styve, 1992). Further details within a country are not available. Moreover, data and computational constraints require simplifications, which might appear to be too crude for studies focusing on a single country. The results should, therefore, be seen as comparative rather than absolute cost estimates: the emphasis is on international consistency and comparability.

The remainder of the paper is structured as follows. Section 2 describes the major options for controlling ammonia and section 3 describes the method for calculating the costs. Section 4 presents the data with example results presented in section 5. Section 6 provides conclusions and a critical discussion.

2. Options for controlling ammonia emissions in Europe

Major sources of ammonia emissions are: livestock farming (78–81%), fertiliser use (17–19%) and industry (0–2%) (Klaassen, 1991b; Asman, 1992). The following options can be distinguished to control ammonia emissions from livestock farming (see Baltussen et al., 1990a; Hannessen, 1990; Kuik, 1987; Oudendag and Wijnands, 1989):

- changes in the nitrogen content of fodder (such as multiple stage foddering);
- adaptations during the stabling and storage of manure:
  - stable adaptations (such as manure flushing);
  - covering manure storage;
  - cleaning of stable air (bio filtration or scrubbing);
- low ammonia application (e.g., direct ploughing down of manure).

Changing the nitrogen content of the fodder affects the ammonia emissions of three processes: stable and storage of manure, application, and in the grazing period. Adaptations to stable and storage affect both stable plus storage emissions, as well as emissions during application, since the nitrogen content of the excretion may increase. In several branches of the chemical industry emission reductions can also be achieved through the application of stripping and absorption techniques (Tangena, 1985). Table 1 presents the abatement options distinguished in RAINS. Including combinations of the various abatement techniques, 48 different options are available (Klaassen, 1991a). Although in principle more combinations are conceivable,

Table 1 *Abatement options for ammonia emissions and removal efficiencies (%)*

LIVESTOCK FARMING					
Options per process	Fodder	Stable and storage			Application
	Low-N fodder (LNF)	Stable adaptation (SA)	Closed storage (CS)	Biofiltration (BF)	Low NH_3 application (LNA)
Animal type					
Dairy cows	20–25	50	10		90
Other cattle			10		90
Pigs	15	65		90	90
Laying hens	10	60	80	80	90
Other poultry	20	90	80	80	90
Sheep					
Horses					
INDUSTRY					
Stripping/absorption					50

some of them are technically not possible and others remove less emissions at more costs than other combinations.

3. Method for estimating costs

3.1. Low nitrogen feed, stable adaptations, covering manure storage and cleaning stable air

Low nitrogen feed is a combination of various techniques to reduce emissions, such as:
– reductions in the level of nitrogen applications on grassland or the substitution of grass by silage maize for dairy cows (Baltussen et al., 1990b; Spiekers and Pfeffer, 1990);
– reductions in the nitrogen content of feed through either an improved agreement between the amino acids in the diet and the amino acid requirements of animals (multi-phase feeding), or changes in the composition of the raw materials and supplementing diets with synthetic amino acids for pigs and poultry (Baltussen et al., 1990a; Lenis, 1989; Spiekers and Pfeffer, 1990).

For various animal categories, low-emission stable systems exist that limit the escape of ammonia. NH_3 emissions from stalls can be reduced by limiting the time that manure remains in the stable, keeping floors as dry and free of manure as possible, drying manure quickly, minimising the time during which ammonia is in contact with the air, or adding acid to manure (Hannessen, 1990). The preliminary cost estimates used in this study are based on the following systems:

- dairy cows: stable washing and scraping systems, removing manure regularly to a (closed) storage basin;
- pigs: manure flushing and scraping systems;
- laying hens: manure belt with forced drying of manure;
- broilers: forced drying of littered, slatted floor.

For most of these systems, especially for pigs and dairy cows, cost estimates are uncertain since hardly any practical experience exists.

Covering manure storage facilities is another way to prevent the escape of ammonia during storage. A third option to control the emissions from the stable is the application of various techniques that clean the stable air. These techniques can only be applied when stables are equipped with mechanical ventilation. This is usually the case for poultry but not always for pigs (Asman, 1992). Techniques for mechanical ventilation are bio filtration, bio scrubbing and chemical scrubbers. The application of bio filtration for poultry stables may be difficult due to dust problems.

The algorithm used in the cost calculation routine includes technology-specific and animal-specific, as well as country-specific, factors for comparing the costs of abating ammonia emissions per country (for details see Klaassen, 1991a). The costs for each control technique consist of (annualised) investment costs, and fixed and variable operating costs. Investments are a function of the stable size and are annualised over the lifetime of the installation using an interest rate. Fixed annual operating costs are a fixed percentage of the investments. Depending on the technique, variable operating costs consist of the following elements: increase in feed costs per animal due to higher prices of low nitrogen feed compared to normal fodder, the costs of using natural gas (heating), electricity, water and labour, and waste-disposal costs.

Based on the above mentioned items the average costs for each option to control NH_3 emissions are calculated. These amounts are expressed in costs per animal per year by taking into account the number of animal rounds per year and the capacity utilisation factor. The cost efficiency of the abatement options is evaluated by relating annual costs to the volume of emissions reduced to obtain the cost per unit of NH_3 removed. In doing so, it is taken into account that abatement options may simultaneously reduce emissions during stable period, application and in the meadow. The volume of emissions reduced not only depends on the removal efficiency of each option, but also on the unabated emissions for animal type in the meadow, the stable, or during application. These emission coefficients are country-specific and depend, for example, on the stable period.

3.2. Low-ammonia application of manure

A wide variety of techniques exists to prevent the escape of ammonia during manure application on arable land or grassland (Huijsmans, 1990; Krebbers, 1990; Havinga, 1992):

- direct application (ploughing down) of manure on arable land;
- manure injection (deep) on grassland;
- sod injection (shallow) or sod manuring for manure on grassland;
- sprinkling, trenching or diluting manure on grassland.

Furthermore, processing manure to control manure surpluses, as a side effect, reduces ammonia emissions during application. This option, however, is less likely in countries where the manure surplus is less of a problem than in the Netherlands. In addition, the costs of manure processing are too high to justify its application for controlling ammonia emissions only.

The applicability of these techniques (apart from manure processing) depends, among other things, on soil type, water availability (sprinkling), and the slope of the soil. Sod manuring can be applied on soils with low carrying capacity (heavy clay or peat soils) where manure injection may not be feasible. Dilution of manure is partly practiced in Alpine countries and may be more appropriate for soils in steeply sloped areas.

The cost calculation method expresses costs per cubic meter of manure applied since these techniques are usually carried out by contractors whose services can be rented by the individual farmer. In addition, this avoids unnecessary complications in the cost calculation routine. Costs per cubic meter of manure depend on, among other things, the technique, the volume of manure applied per hectare and the distances between land and storage (Krebbers, 1990; Havinga, 1992). The most important country-specific element is probably the mixture of techniques. Not only are there additional costs but there are also cost savings since less artificial fertiliser has to be applied. It is also possible that, because of the poor uptake of phosphate from injected manure, an additional amount of phosphate fertiliser will have to be applied at the start of the growing season.

The calculation distinguishes the fixed costs and the variable costs per cubic meter of the mixture of techniques (ploughing down, manure injection, sod manuring, sprinkling or manure processing) minus the cost savings. The costs of direct application, manure injection and sod manuring per cubic meter are a function of the volume of manure applied per hectare. The costs of sprinkling per cubic meter of manure depend on the manure production per farm, a function of the stable size. The costs of manure processing are not fully attributed to ammonia emission control since the technique is primarily directed at controlling nitrate and phosphate surpluses. The cost savings due to a reduction in fertiliser use depend on: the emission coefficient for application; the removal efficiency of application; the country-specific fertiliser price; and the share of manure processed. The ammonia that is not emitted does not fully lead to equal savings in fertiliser. Krebbers (1990) is of the opinion that the effectiveness of the nitrogen uptake by grassland increases by a factor of two. Therefore only half of the ammonia is assumed to lead to savings in fertiliser use. For that part of the manure that is processed there are no savings in fertiliser use. Based on the above mentioned items, the cost efficiency of the abatement option is evaluated again by relating the annual costs to the volume of emission reduced; this then gives the cost per unit of NH_3 removed.

3.3. *Industrial ammonia emissions*

The production of ammonia and nitrogen fertilisers are important industrial sources of emissions. The application of stripping and absorption techniques can reduce such emissions. The annual pollution control costs are calculated as the product of the unabated emissions, the percentage removed and the (exogenously determined) average costs per ton of ammonia abated (Tangena, 1985). This simplified scheme is used since the contribution of industrial ammonia emissions to total emissions is negligible.

4. **Data on costs**

4.1. *Costs of low nitrogen feed*

The nitrogen excretion of dairy cows can be lowered if the level of nitrogen application on grassland is reduced from 400 or even 500 kg nitrogen per hectare to 200 kg nitrogen per hectare and grass silage is partly substituted by silage maize, according to Baltussen et al. (1990b) for the Netherlands. Their calculations show that reductions in stall emissions by 10 to 30 per cent and in meadow emissions of around 25 per cent for dairy cows are possible. Spiekers and Pfeffer (1990) indicate that a reduction of 10 to 15 per cent in nitrogen excretion would be possible. Whether this alternative is possible in other European countries, with the exception of Denmark and Germany, is uncertain since the levels of nitrogen application on grassland in other European countries are generally far below that of the Netherlands. Consequently, the user of RAINS is allowed to limit the potential applicability of this alternative.

For pigs, multi-phase feeding, in combination with nitrogen poor feed or synthetic amino acids, reduces nitrogen in the excretion by 5 per cent for fattening pigs and 20 per cent for sows (Baltussen et al., 1990c). Spiekers and Pfeffer (1990) even suggest that reductions of up to 35 per cent are possible for fattening pigs and 15 per cent for sows. Lenis (1989) is of the opinion that synthetic amino acids may achieve reductions of 25 per cent for both pigs and sows in the long term.

For laying hens a reduction in the albumen content may reduce the nitrogen excretion by some 10 per cent. Multi-phase feeding and synthetic amino acid are expected to reduce the nitrogen excretion for broilers by 20 per cent (Van Horne, 1990).

Implementing low-nitrogen feed only requires investments for pigs: for multi-phase feeding an elevator and cart are required. Introducing multi-phase feeding for poultry requires no such investments since animals of the same age are present in the stable (Van Horne, 1990). However, the costs for all animal categories will consist of higher fodder prices. The technology- and animal-specific data are presented in Klaassen (1991a). Data are based on Baltussen et al. (1990a, 1990b, 1990c) and Van Horne (1990). The investment costs are annualised over the lifetime of the installation using the interest rate. There are no fixed operating costs. Variable operating costs consist of the increase in feed costs per animal due to the higher prices of low-nitrogen feed. These costs are based on changes in the composition of the raw materials for feed production in the Netherlands. Results for Germany (Spiekers and Pfeffer, 1990), however, show that, for pigs, the cost increases in the Netherlands and Germany are comparable.

4.2. Costs of stable adaptations

Washing the stable floor of dairy cow stables and frequently removing the manure to a closed-storage system can reduce ammonia emissions by 50 to 70 per cent (Oosthoek et al., 1991). Costs consist of the washing system in combination with manure storage capacity (Baltussen, 1990b). For pig stables, Oosthoek et al. (1990, 1991) conclude that the reduction in ammonia emissions is 60 to 70 per cent. This is based on a manure flushing system in combination with a replacement pump or drainage system in the stable. Provisional cost estimates were made by Baltussen et al. (1990c) and Hakvoort and Paques (1989). The application of a manure belt with forced drying of manure reduced emissions from the stables of laying hens by some 60 per cent (Van Horne, 1990; Kroodsma et al., 1990). Forced drying of slatted, littered floors or trampoline systems are expected to reduce ammonia emmisions from broiler housing systems by 90 per cent (Boonen, 1990). Costs mainly consist of additional investments, costs of recirculating air, energy and litter use.

The investment function for stable adaptations is the same as for low nitrogen feed. The technology- and animal-specific data are presented in Klaassen (1991a). For cow sheds and pig sties the investments depend on the stable size. These relationships should be regarded as tentative, in view of the lack of experience. Fixed operating costs are a fixed percentage of the investment. Due to a lack of experience with these techniques generally no specification of the variable operating costs for pigs and dairy cows was possible yet. Variable operating costs consist only of the additional heating costs of using natural gas for laying hens.

4.3. Covering manure storage

Covering the storage of manure prevents 90 per cent of the ammonia emissions (Baltussen et al., 1990b). Since only part (some 10 per cent) of the total ammonia released during stable and storage actually escapes from the storage, the overall removal efficiency is only 10 per cent. Costs consist of investments only of the roof or the cover minus the smaller investments in the silo. The silo can be smaller since no rain enters the silo. The investments depend on the size of the silo (Klaassen, 1991a). Storage covering is only feasible if storage facilities already exist or are expected as a result of national legislation.

4.4. Cleaning stable air (bio filtration or scrubbing)

Another possibility to control stable emissions is the application of techniques that clean the stable air, such as bio filtration, bio scrubbing and chemical scrubbers. The removal efficiency is generally very high: 80 to 90 per cent of stable emissions are removed. Cost estimates vary widely (Klaassen, 1991a), and the investment depends on the size of the installation (Jol, 1990; Klaassen, 1991a).

Fixed operating costs are again a fixed percentage of the investments. No country-specific prices are incorporated for labour, water and waste disposal due to a lack of data on the one hand, and the fact that these cost items are generally less relevant for total annual costs than capital costs and (country-specific) electricity prices.

4.5. Low ammonia application of manure

Direct application of manure, or ploughing down, can reduce ammonia emission by 80 to 90 per cent in comparison to surface spreading. The removal efficiency of manure injection is 90 to 99 per cent. The reduction to be achieved by sod manuring, or shallow injection, varies between 75 and 99 per cent. Sprinkling, trenching or the dilution of manure has a removal efficiency of 75 to 90 per cent (Havinga, 1992; Huijsmans, 1990; Huijsmans and Bruins, 1990; Krebbers, 1990). When manure is processed the reduction is 100 per cent.

The net costs for direct application are DM 0.00 to DM 7 per m^3 and for manure injection DM 0.00 to DM 5 per m^3. Sod manuring costs vary between DM 3 and DM 7 per m^3. Sprinkling is more expensive: costs are DM 6 to DM 18 per m^3 (Baltussen et al., 1990b; Krebbers, 1990; Huijsmans, 1990; Havinga, 1992). Manure processing costs around DM 25 to DM 35 per m^3 (Stoop, 1989; Reichow and Yawari, 1990; Vroege, 1990).

The total annual cost of low ammonia application techniques depends on the costs per ton of manure applied for each of these techniques, the shares of manure directly applied, injected, sod manured, sprinkled, processed, the production of manure per animal, and the savings in fertiliser costs (Klaassen, 1991a). Country-specific elements are: the shares of the different low-ammonia application techniques; the volume of manure per hectare and the fertiliser price; and the manure production per animal (Klaassen, 1991a). As default values the share of manure ploughed down is assumed to be equal to the share of arable land, and the share of manure injected is equal to the share of grassland in each country (FAO, 1989). For the time being the default value for the shares of sod manuring and sprinkling are set at zero due to a lack of data. Manure processing is assumed to take place only in the Netherlands (8 per cent of the manure; Vroege, 1990). Since the cost of manure processing is much higher than the other techniques it is not applied for ammonia control but geared towards controlling manure (mineral) surpluses. Therefore, the fraction of the costs of manure processing attributed to ammonia control is zero by default.

4.6. Costs of combinations and industrial process emissions

The options which are available per animal category (see Table 1) can also be applied in combination. In that case the costs per animal per year are simply the sum of the costs of the separate options, but the removal efficiencies of the combinations are less or equal than the sum of the removal efficiencies of the separate options. For example, low-nitrogen feed for dairy cows may reduce ammonia emissions during application by 20 per cent. Manure injection may reduce application emissions by 90 per cent. In combination, however, the reduction is only 92 per cent. Details on the combinations and their removal efficiencies are given in Klaassen (1991a). The removal efficiencies of these combinations are calculated using nitrogen balances for each animal type.

The total annual costs of controlling ammonia emissions from industrial processes are estimated at DM 1250 per ton NH_3 removed, for removing 50 per cent of the unabated emissions (Tangena, 1985).

5. Results

5.1. Average costs per ton emission abated

RAINS offers the user two possibilities to estimate emission reductions:
- scenario analysis: calculating the costs and emissions of a variety of combinations of control options on any part of the emissions;
- optimisation: i.e., reaching emission or deposition targets at minimal costs.

For the scenario analysis, the user is free to specify which number of animals have to apply specific control options. This allows the user, for example, to calculate what the impact would be of low ammonia application for all animals on sandy soils only. Due to limited space, this study will only describe a few examples, a complete listing can be obtained from model runs.

Table 2 shows the average costs per animal per year and the costs per ton ammonia of low ammonia application for pigs, and stable adaptations for dairy cow sheds. The annual costs of low ammonia application per pig differ at most by a factor of 2.5. The differences are explained by:
- the relative shares of the different low-ammonia application techniques in the volume of manure spread (direct ploughing down, manure injection and manure processing);
- the volume of manure per hectare;
- the emission coefficient for application of pig manure;
- the fertiliser price.

The first two elements determine the costs per cubic meter of manure, whereas the latter two influence the savings in the costs of fertiliser use. The costs per ton ammonia are not only affected by the costs per animal per year but also by the (country-specific) emission coefficient for application. At present, these differences are only of minor importance for pigs. They are more relevant for other animals, especially dairy cows.

The costs of stable adaptations for dairy cows per animal per year differ roughly by a factor of two and a half. These cost differences are caused by 'economies of scale' expressed in the size of the stable (dairy cows per shed).

Table 2 *Average costs of low ammonia application for pigs and stable adaptation for dairy cows*

	Low ammonia application: Pigs		Stable adaptation: Dairy cows	
Country	DM/animal per year	DM/t NH_3	DM/animal per year	1000 DM/t NH_3
Albania	8.26	3220	161	49
Austria	6.11	2349	190	45
Baltic region	7.80	3043	163	56
Belgium	4.13	1536	179	65
Bulgaria	9.40	3666	168	51
Byelorussia	7.80	3043	163	56
CSFR	9.08	3541	159	33
Denmark	9.10	3860	177	39
Finland	9.67	3951	204	30
France	8.87	3422	181	61
FRG-West	7.03	2761	192	36
FRG-East	7.81	3045	159	43
Greece	10.17	4265	413	13
Hungary	10.62	4140	162	55
Ireland	7.16	2715	180	60
Italy	10.08	4227	232	74
Luxembourg	5.09	1910	169	47
Moldavia	7.80	3043	163	56
Netherlands	4.01	1562	163	37
Norway	6.39	2493	216	43
Poland	9.70	3783	216	65
Portugal	9.00	3510	345	109
Rem. Eur. Russia	7.80	3043	163	56
– Kola Karelia	7.80	3043	163	56
– St. Petersburg	7.80	3043	163	56
Romania	9.23	3598	166	50
Spain	9.88	3839	304	100
Sweden	9.18	3579	183	41
Switzerland	6.85	3200	210	37
Turkey	9.68	3776	413	166
UK	7.43	2193	156	49
Ukraine	7.80	3043	163	56
Yugoslavia	9.11	3552	216	71

The costs per ton ammonia abated show a wider range since the emission coefficients for the stable period show a wide range (Klaassen, 1991a). For example, in Finland the volume of ammonia emitted per cow per year during the stable period is higher than in Austria. This is mainly because the stable period is longer. As a result the costs per ton ammonia abated in Finland are lower (DM 30,000 per ton) than in Austria (DM 45,000 per ton). The higher (fixed) costs per animal per year (Finland DM 204 per cow versus Austria DM 190 per cow) are more than compensated for by a higher volume of emission abated per cow which reduces the costs per ton ammonia controlled. Due to the limited accuracy of the underlying statistics, especially for Eastern Europe, and the limited availability of cost data for some of the control options (e.g., stable adaptations) the magnitude of the observed variations might be questionable. Still, it seems better to introduce such differences rather than to ignore them.

5.2. Cost functions and cost minimisation

For the optimisation mode in RAINS it is necessary to create 'national cost functions' for controlling ammonia. These cost functions can also be employed to determine cost-effective strategies for reducing nitrogen deposition in Europe. As shown in the previous section, national circumstances result in variations in the costs for applying the same technology in different countries in Europe. Another source of difference is to be found in the structural differences between the agricultural systems, especially in the structure of the livestock population and the intensity and type of fertiliser 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 ranking the options according to their marginal costs and their individual potential for removal.

Example results of such national cost functions for ammonia are given in Figure 1. They are based on national forecasts for the year 2000. Livestock population and fertiliser consumption are either based on national forecasts

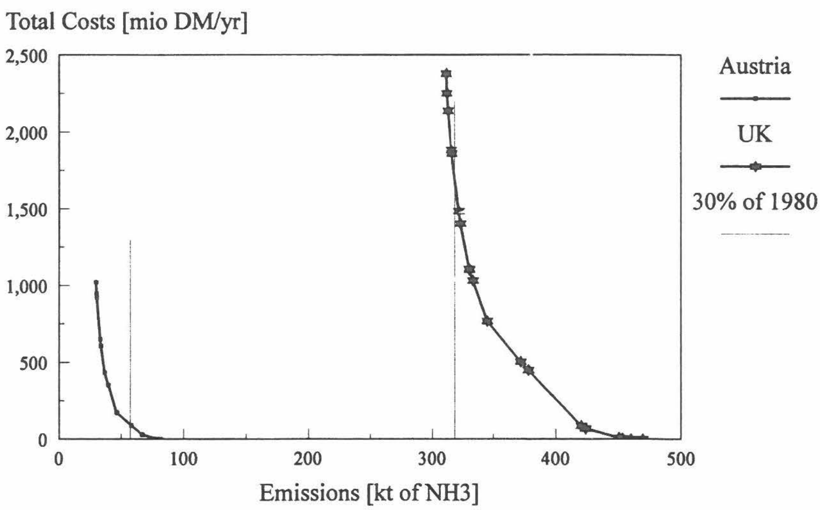

Figure 1. *National cost functions*

from agricultural research institutes and universities, or trends observed in the period 1979–1988 were extrapolated and, where necessary, adjusted to bring them in line with OECD and EC forecasts (Klaassen, 1991b). The two curves describe the total costs as a function of the remaining ammonia emissions in the year 2000. The figures clearly show that the national cost functions differ between countries. In Austria a 30 per cent reduction of 1980 ammonia emissions (bringing them down to 60 kton NH_3) would be relatively cheap (around DM 100 million per year) and marginal costs would be low (DM 7,000 per ton NH_3). This is mainly because:

1. Austria's emissions are expected to remain stable between 1980 and the year 2000.
2. A large part of the emissions can be removed by applying low nitrogen manure at relatively low costs (cf. Table 3).

In the United Kingdom, however, measures for a 30 per cent cutback would be more costly: annual costs would be DM 1,700 million per year for reducing emissions to some 320 kiloton NH_3. This is 17 times higher than

Table 3 *National cost function Austria (year 2000)*

Control option	NH_3 removed (kton)	Marginal costs (DM/ton NH_3)	Annual costs (million DM)	Remaining NH_3 (kton NH_3)	Total annual costs (million DM)
Unabated NH_3				81.8	0
OP: LNA	0.85	−305	−0.3	81.0	−0.3
LH: LNA	1.41	548	0.8	79.6	0.5
INDSTRIP	0.39	1250	0.5	79.2	1.0
PI: LNA	11.82	2348	27.8	67.3	28.8
LH: SA + LNA	0.73	5633	4.1	66.6	32.9
OC: LNA	8.36	6879	57.5	58.2	90.4
DC: LNA	11.31	7031	79.5	46.9	169.9
OP: SA + LNA	0.54	9022	4.9	46.4	174.7
LH: LNF + SA + LNA	0.06	25230	1.6	46.3	176.4
PI: SA + LNA	6.86	26256	175.3	39.7	351.7
DC: LNF + LNA	3.04	26720	81.4	36.6	433.0
DC: LNF + SA + LNA	3.07	55990	171.7	33.6	604.7
OP: LNF + SA + LNA	0.03	66256	2.0	33.5	606.7
OC: CS + LNA	0.54	79799	43.5	33.0	650.2
PI: BF + LNA	2.57	105210	270.5	30.4	920.7
LH: LNF + BF + LNA	0.22	125398	27.5	30.2	948.2
PI: LNF + BF + LNA	0.34	214246	72.2	29.9	1020.3

DC: dairy cows	LNA: low ammonia application of manure
OC: other cattle	SA: stable adaptations
PI: pigs	LNF: low nitrogen fodder
LH: laying hens	CS: covered manure storage
OP: other poultry	BF: biofiltration
	INDSTRIP: industrial emission control

in Austria although the volume of emissions controlled is only six times higher. There are two major reasons for the higher costs in the UK:
1. Emissions in the UK are expected to increase slightly between 1980 and 2000 so that more emissions have to be removed to attain a 30 per cent cutback.
2. The composition of UK ammonia emissions is such that a large share comes from sources not controlled in this study: sheep, goats and fertiliser. Consequently, to meet the 30 per cent cutback more costly measures are necessary in the remaining sectors (poultry, pigs, dairy cows) driving up the marginal costs to more than DM 63,000 per ton NH_3 removed.

5.3. *Costs of several scenarios*

The national cost functions can be used to evaluate the costs of several scenarios to control ammonia emissions in Europe. For this analysis the following scenarios were selected:
1. No control (unabated emissions) in the year 2000;
2. A 30 per cent reduction over 1980, comparable to existing agreements for SO_2 emissions;
3. A regulatory scenario, assuming that all countries will prescribe low-ammonia application techiques for all animals, the covering of manure storage facilities for dairy cows and other cattle and will reduce industrial emissions by 50 per cent;
4. A cost-effective scenario, which starts from the same national emission levels of scenario 3 (the regulatory approach) but allows achieving this emission level at minimum costs for each country. This is comparable to agreeing on a cap on total national emissions and leaving countries free to achieve this;
5. Maximum technically feasible reduction.

Table 4 shows the ammonia emissions in the year 2000 under the various scenarios. As can be seen, unabated emissions in the year 2000 in Europe would increase by 2 per cent over 1980. Emissions are expected to decline or stabilise in the EC-North, Scandinavia and Alpine countries (Austria, Switzerland). An increase is generally expected in the EC-South and in Eastern Europe. A 30 per cent flat rate would reduce emissions to around 5,900 kilotons. For some countries (Albania, Bulgaria, Greece, Ireland, Spain) a 30 per cent reduction would not be possible. This is because either the unabated emissions rise sharply from 1980 to 2000 (Greece), and/or the dominating sources are those for which no abatement options are available (sheep, fertiliser) or for which only options with limited removal efficiency (other cattle) are available. The regulatory approach (scenario 3) would limit Europe-wide emissions to some 5,800 kilotons in the year 2000, a reduction of some 30 per cent compared to 1980. The cost-effective scenario (4) has the same national emission levels as the regulatory approach. If all abatement

Table 4 *Ammonia emissions in 2000*

	Base year 1980	Unabated emission 2000	30% reduction of 1980	Regulatory approach	After maximum technically feasibile reduction	
Country	(kton)	(kton)	(kton)	(kton)	(kton)	(% 1980)
Albania	26	34	18	26	24	8
Austria	81	81	57	46	30	63
Belgium	103	92	72	54	33	68
Bulgaria	123	143	86	106	88	28
CSFR	195	187	137	117	89	54
Denmark	121	85	84	50	31	74
Finland	62	44	34	28	26	58
France	710	685	497	481	403	43
FRG-West	584	608	409	489	299	49
FRG-East	227	176	159	106	74	67
Greece	77	110	54	96	86	−12*
Hungary	149	153	104	107	79	47
Ireland	131	161	92	116	105	20
Italy	384	392	269	284	236	38
Luxembourg	5	5	3	3	3	40
Netherlands	265	247	186	144	81	70
Norway	40	34	28	22	18	55
Poland	514	404	359	291	232	55
Portugal	65	61	46	45	38	32
Romania	292	418	204	269	192	34
Spain	262	427	183	319	256	2
Sweden	68	61	48	37	24	65
Switzerland	65	53	45	28	23	65
Turkey	526	402	368	334	305	42
UK	454	469	318	349	312	31
Yugoslavia	212	215	148	144	104	51
Kola-Karelia	5	6	4	4	3	40
St. Petersburg	46	48	32	30	22	52
Baltic region	158	160	110	105	81	49
Byelorussia	193	219	135	146	119	38
Ukraine	755	748	529	484	379	50
Moldavia	46	48	32	31	23	50
Rem. Eur. CIS	1443	1514	1010	1023	824	43
Europe	8404	8506	5883	5831	4642	45

% 1980 implies per cent reduction to 1980 emission.
* − means increase.

options could be applied in any situation (full potential) Europe-wide, a 45 per cent reduction in ammonia emissions would be the maximum achievable.

The costs of the scenarios are presented in Table 5. The table shows that the total European costs of a 30 per cent flat rate reduction, would be

Table 5 *Costs of various scenarios (million DM/year in 2000)*[b]

Scenario country	30% reduction of 1980	Regulatory approach	Cost-minimum	Maximum feasible reduction
Albania	128[a]	63	0	128
Austria	98	284	176	989
Belgium	22	151	105	921
Bulgaria	876[a]	281	166	867
CSFR	237	463	386	1387
Denmark	0	212	177	1027
Finland	0	141	191	315
France	1353	2072	1530	4885
FRG-West	864	1489	1074	5068
FRG-East	34	388	328	1590
Greece	525[a]	205	47	525
Hungary	257	266	214	1316
Ireland	986[a]	594	460	986
Italy	1026	1297	740	3126
Luxembourg	8	15	11	28
Netherlands	65	262	170	1770
Norway	17	97	52	223
Poland	140	1357	758	3569
Portugal	82	312	88	652
Romania	2432	863	673	3484
Spain	4747[a]	1458	679	4847
Sweden	40	162	124	641
Switzerland	25	186	192	498
Turkey	144	2869	616	3150
UK	1715	845	720	2255
Yugoslavia	364	777	413	2143
Kola-Karelia	12	15	11	38
St. Petersburg	67	126	92	354
Baltic region	263	408	314	1310
Byelorussia	682	551	420	1479
Ukraine	1007	1937	1471	5672
Moldavia	69	100	74	366
Rem. Eur. CIS	2849	3616	2716	10509
Europe	21241	23826	15205	66132

[a]Costs of maximum feasible reduction.
[b]Costs in constant DM of 1990.

DM 21 billion per year. The regulatory approach would cost DM 24 billion annually. The cost-effective solution for the same national levels of emissions as the regulatory approach (scenario 3) would reduce costs to DM 15 billion per year. Clearly, because of large differences in potential and costs for the same control option among countries, leaving countries the freedom to choose their own cost-effective strategies would be considerably cheaper. The maximum reduction would cost DM 66 billion per year.

The RAINS model can also be used to show the impact of emission reduction strategies on the nitrogen deposition due to NH_3. Figure 2, for example, shows the nitrogen deposition resulting from a uniform 30 per cent cutback. Clearly, in this case deposition would still remain high in regions were livestock farming is concentrated, such as the eastern part of the Netherlands and north-west Germany. The regulatory approach would lead to a similar Europe-wide level of emissions as the 30 per cent cutback. The distribution of emission reductions would, however, be different. The regulatory approach would reduce nitrogen deposition in the eastern part of the Netherlands to below 2 gram $N/m^2/yr$ whereas a 30 per cent flat rate would still allow peaks of between 2–4 gram $N/m^2/yr$.

6. Conclusions and discussion

The results of this study suggest that:

1. The average costs of applying the same technical options to control ammonia emissions in Europe differ considerably among countries due to country-specific factors;
2. Differences in the structure of livestock population, the contribution of mineral fertiliser to total ammonia emissions, as well as differences among countries in expected growth, imply that uniform cutbacks may not be feasible in every country and, if feasible, the costs differ considerably; maximum technically feasible reductions differ considerably as well;
3. Due to differences in average costs and agricultural structure, a regulatory approach, prescribing the same techniques in every country, is expected to be more expensive than setting country-specific emission ceilings. Future international agreements to control ammonia emissions should prescribe national emission ceilings rather than emission reduction techniques.

The above conclusions are subject to a number of qualifications: uncertainty on livestock and fertiliser projections, underestimation of emission reductions, the extent to which cost estimates can be transferred to other countries, the relevance of reducing the livestock size as a cost-effective control option, the impact of reducing ammonia on groundwater pollution, and the spatial distribution of ammonia emissions within countries.

First of all, projections on livestock population, fertiliser use and ammonia emission coefficients determine the level of uncontrolled emissions in the year 2000. Forecasts might vary as a result of changes in population growth, income per capita performance, agricultural policy and consumer preferences. It seems advisable to improve the existing reference scenario and create alternative projections.

Secondly, the emission reduction that can be achieved might be underesti-

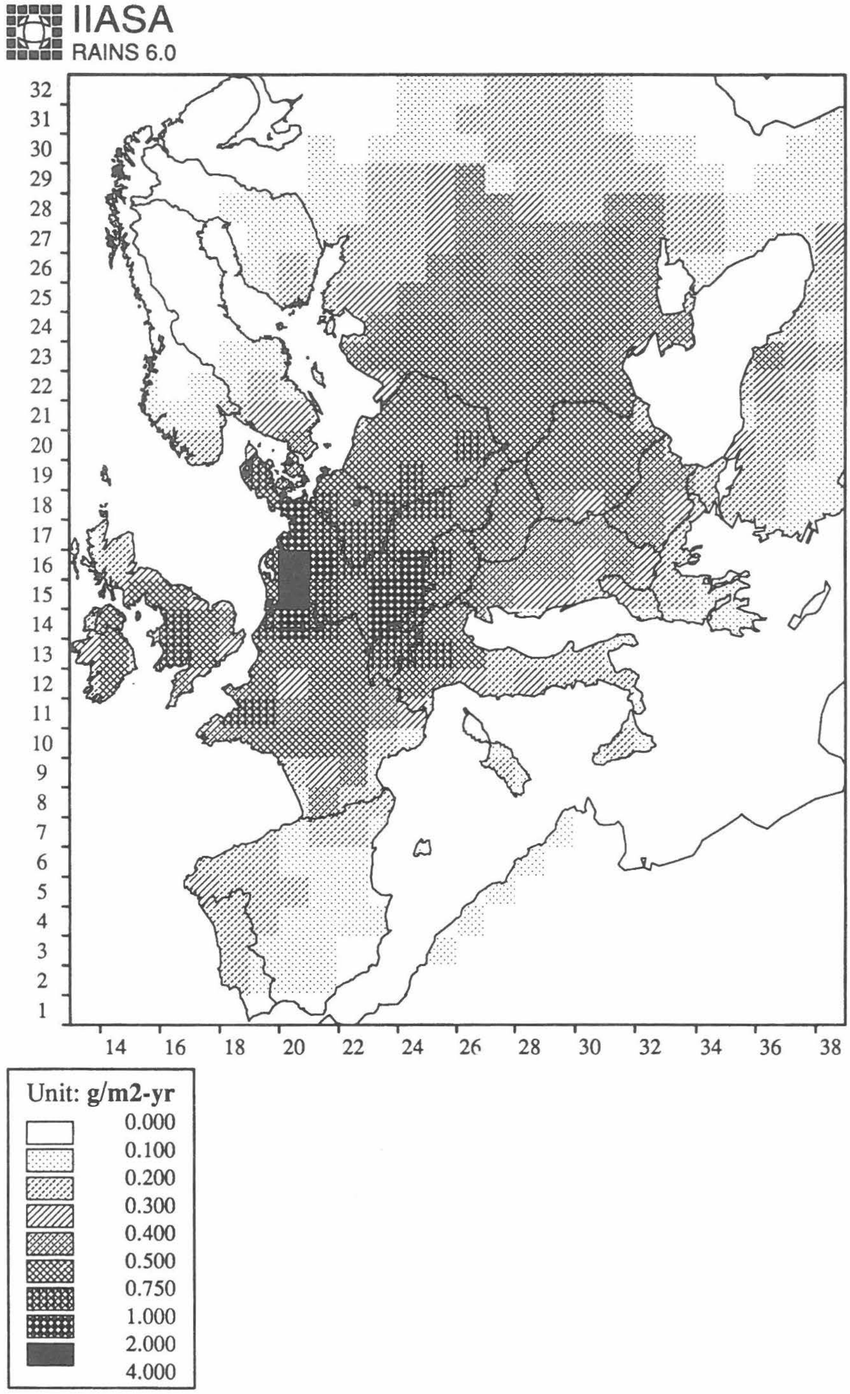

Figure 2. *Nitrogen deposition after a 30% flat rate reduction*

mated since for some animal types within the category 'other cattle', techniques are possible with higher removal efficiencies (e.g., bio filtration for fattening calves), but neither national nor international statistics supply data on the number of these types of animals. Moreover, as a secondary effect, emissions from fertiliser use will decline when low ammonia application techniques are applied. Finally, although fertiliser use is conceived as uncontrollable in this study, it is thinkable that options such as fertiliser taxes could be used to reduce fertiliser consumption.

Thirdly, one might question whether the results on costs and removal efficiency, based on recent experience in the Netherlands and Germany, can be transferred to other countries. Regarding low ammonia manure application techniques, experts agreed that their application is not universal (Klaassen, 1992). In Finland, for example, clay soils do not permit the use of heavy machinery on grassland. In Switzerland, the slope of the soil and the presence of stones might pose physical limitations. Direct application of manure on arable land however seems less problematic than the injection of manure on grassland. Regarding low-nitrogen feed (Klaassen, 1992) for dairy cows, shifts to low-nitrogen feedstuffs might be restricted, especially in countries where nitrogen input is already low. Concentrate use could, however, be reduced in Germany, the Netherlands, Denmark and the United Kingdom. For pigs and poultry, the possibilities to alter the fodder composition to reduce the nitrogen content are more universally applicable. Stable adaptations are believed to be universally applicable although country-specific modifications might be needed (Voermans, 1992). Bio-filtration or similar techniques cannot be applied in stables with natural ventilation. The user of the RAINS model can reduce the potential applicability of techniques in each country to examine the impact on control costs and emission reduction potential. If the potential application of a number of techniques were to be restricted (Klaassen, 1991b), a 30 per cent flat rate reduction could cost DM 32 billion instead of DM 21 billion per year, since countries would have to adopt more expensive techniques. A second issue is whether cost estimates sufficiently account for country-specific circumstances. In the author's opinion, the most relevant factors are included, but the most uncertain elements are not only the potential applicability of some techniques but also the ammonia emission coefficients since these are not always country-specific.

Fourthly, studies suggest that reducing the livestock size might be a more cost-effective strategy to reduce ammonia emissions (Stolwijk, 1989; Stolwijk et al., 1992). Stolwijk (1989) concludes that the cost of emission reductions might be so high that a number of farmers will stop farming. For example, a maximum feasible reduction by technical means in the Netherlands would cost 21,000 guilders per ton ammonia removed. Accounting for the negative impact of these costs on the size of the livestock sector reduces costs to 6,000 guilders per ton ammonia abated (Stolwijk, 1989: 32–34).

Consequently, the RAINS approach might overestimate the direct costs of reducing ammonia emissions and underestimate emission reductions since indirect impacts are ignored.

Fifthly, depending on the effectiveness of nitrogen uptake, the application of techniques to reduce ammonia emissions, such as manure injection, might lead to an increase in soil and groundwater pollution. To limit these impacts, manure spreading has to take place in the growing season and the amount has to be adapted to the needs of the vegetation. So, strategies for controlling ammonia emissions have to account for side impacts on soils and groundwater pollution.

Finally, ammonia emissions are heavily concentrated in certain areas within countries. In view of the fact that around 50 per cent of ammonia is deposited within 100 kilometers of the source (Asman and van Jaarsveld, 1992) it might be much more cost-effective to reduce ammonia emissions in specific regions within a country. Although this is a correct approach for one country, it is not feasible Europe-wide since available atmospheric models currently only allow calculation of the ammonia emissions from 33 countries to more than 500 grids in Europe, but do not permit calculating from regions (or grids) within a country to each grid (Sandnes and Styve, 1992). So the knowledge does not exist to determine in which grids emissions have to be reduced to achieve grid-specific nitrogen-deposition objectives, let alone that the grid-specific cost information is available to meet such objectives at minimum cost.

In spite of the limitations to the approach followed in this study, the main conclusions are not affected. Both structural as well as country-specific elements imply considerable differences in the potential and costs of controlling ammonia emissions in each country. Leaving countries the freedom to achieve national emission reduction is thus more cost-effective than a regulatory approach. The order of magnitude of the suggested differences is, however, subject to uncertainty.

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