Status Report

Estimating Emission Control Costs: A Comparison of the Approaches Implemented in the EC-EFOM-ENV and the IIASA-RAINS Models

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Otto Rentz**, Martin Wietschel**

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Preface

Estimating pollution control costs is not only an important theme in the field of environmental economics, but also provides essential information for the design of cost-effective emission control strategies. A variety of methods to assess pollution control costs exist in the literature.

Energy combustion is the major source of emissions of transboundary pollutants SO_2 and NO_x that contribute to acidification in Europe. This paper compares two different methods to estimate the direct costs of reducing SO_2 and NO_x emissions on a macro-economic level:

With energy flow optimization models (such as MESSAGE, MARKAL or EFOM-ENV) reactions of energy supply systems to increasingly constrained overall emission levels can be analyzed, and thereby the incremental costs caused by environmental constraints can be explored. Such models have the advantage that they encompass wide areas of the energy system; emission control options are not limited to add-on technologies, but incorporate also structural changes (such as energy conservation and fuel substitution) in the analysis. The operation of such models is time and resource intensive and therefore in many cases only a limited number of alternative scenarios can be studied.

Integrated assessment models, such as the RAINS model, derive national costs of emission reduction strategies with a different approach. Simplifications are made through an aggregated representation of the available options for emission reductions and the exclusion of the pollution control potential offered by structural changes of the energy system.

The report suggests that cost estimates obtained by these models are comparable as long as changes in the energy supply structure are excluded from consideration. However, it seems essential to include such options into any comprehensive analysis since in many cases such strategies might offer a significant potential for emission reductions.

The comparison performed in this paper provides important background to discussion on the accuracy of emission control cost estimates.

Peter E. de Jánosi
Director
IIASA

Abstract

The paper introduces two major model approaches to estimate emission control costs and develops a methodology to introduce results of energy flow optimization models (such as EFOM-ENV) into models for integrated assessment of acidification control strategies (such as the RAINS model). Based on a reference scenario for West Germany, national cost curves for reductions of SO_2 and NO_x emissions derived by both the EFOM-ENV and the RAINS model are compared. It is shown that - as long as changes in the energy structure are excluded as means for reducing emissions - results obtained from these models are comparable and the reasons for differences can be traced back to different input assumptions. However, as soon as energy conservation and fuel substitution are utilized to reduce emissions, the simplified approach implemented in the RAINS model results in an overestimation of emission control costs.

Acknowledgement

The research project on comparing estimates of emission control costs derived by the EFOM-ENV model of the Commission of the European Communities and the RAINS model developed at the International Institute for Applied Systems Analysis has been carried out as a cooperative effort by the Institute for Industrial Production (IIP) at the University of Karlsruhe, Germany, and the Transboundary Air Pollution Project at the International Institute for Applied Systems Analysis (IIASA) in Laxenburg, Austria.

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Contents

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1 Introduction

1.1 The increasing demand on emission reduction strategies

During the last two decades, acidification processes in the environment have caused increasing concern in Europe and North America. Major research projects have focused on the causes, mechanisms and effects of acidification taking into account the transboundary nature of the problem. As a consequence, strategies to partly reduce acidification have been internationally discussed and agreed upon (e.g. Helsinki and Sofia Protocols).

The "Critical Loads" concept was developed in recent years as one guideline for further emission reductions. According to this concept, emissions should be reduced until deposition/concentration levels of air pollutants are attained which, according to current knowledge, result in no harmful impacts on the environment. Preliminary analysis indicates that the achievement of this target will require emission reductions in various regions of more than 90 percent compared to 1980 [14]. These emission reductions are well above the level currently agreed upon and cannot be attained by "add-on" emission control technologies alone. Therefore, the analysis of emission reduction strategies is now entering a phase where both structural changes of energy systems and modified consumer behavior will play an essential role in achieving the levels of acidic depositions currently under discussion.

Meanwhile, the increased concern about global climate change has initiated considerations regarding the reduction of greenhouse gas emissions. Since CO_2, which results mainly from energy combustion, is assumed to be a major greenhouse gas, energy strategies are currently being reviewed according to their potential ability to reduce CO_2 emissions. The technical solutions for CO_2 reduction are still limited; however, structural changes in the energy system provide a major potential for reducing CO_2 emissions.

1.2 Models for assessing emission reduction strategies

In order to develop efficient, environmentally compatible approaches for future energy supply, it seems advisable to consider acidification and climate change together and design comprehensive strategies, rather than seeking partial solutions. The analysis of the complex interrelations can be supported by model calculations. For this purpose two major model approaches have been developed:

- The "systems approach" focuses on alternative options for the future development of entire energy systems taking into account technical, economic and environmental aspects of energy supply and emission generation. Models of this type (e.g. Energy Flow Optimization Model – Environment (EFOM–ENV) [4], [10], [11], [15], Market Allocation Model (MARKAL) [6], [16] Model for Energy Supply System Alternatives and their General Environmental Impact (MESSAGE) [9], etc.) describe the energy flows from the primary energy supply over several conversion stages to the final energy consumption. Emissions are estimated for all combustion processes and may be used as constraints for the optimization procedure. With the help of an optimization routine the (cost-)optimal combination of technologies (from the variety of available conversion techniques) can be identified satisfying the exogenously determined final/useful energy demand and other constraints imposed by the user (e.g. upper limits on emissions).

  The large number of technical details considered by these energy-emission models result in considerable implementation complexity; consequently, the focus of such models is often limited to national energy systems. On the other hand – since these models usually comprise major parts of national energy systems, they are also able to consider structural changes of the system (such as energy conservation and fuel substitution) as means for emission reductions.

However, an analysis of the environmental aspects of energy supply strategies using such models is limited to accounting for and constraining the national emissions of several air pollutants. Such models do not consider the environmental impact of acid deposition on ecosystems, nor can they determine the necessary levels of emission reductions be determined by such models.

- "Integrated Assessment Models" cover a wide range of stages in the acidification process from the sources of emission to regional impacts on the environment [13]. Special emphasis is put on the international transboundary character of the problem, resulting in a simultaneous implementation of the most important aspects for all countries within a large region (e.g. for all of Europe). Therefore, as far as emission control options are concerned, the level of detail that can be maintained by these models is limited and not all features of national energy models can be considered. Models of this type are the Regional Acidification Information and Simulation (RAINS) model of the International Institute for Applied Systems Analysis (IIASA) [1] and the Co-ordinated Abatement Strategy Model (CASM) of the Stockholm Environmental Institute at York, UK [3].

  Reflecting the early phase of the international discussion the emission control options considered by these implementations focus on abatement methods suitable for achieving 'medium-range' emission reductions. This results in a restriction of the methods considered in the model to "add-on" technologies, whereas the potential for emission reductions through structural changes in the energy system is currently excluded from the analysis.

  These models can be used to simulate regional environmental impacts of emission reduction strategies and given a prespecified pattern of energy use they can also be used to determine cost-efficient allocations of emission reductions in order to achieve and maintain regional deposition levels. However, due to the aggregated representation of the abatement options, these estimates exclude some of the possibly most efficient emission control options.

1.3 Objectives and structure of this paper

This paper provides an overview of the results obtained in the first phase of a study on a combination of the two model approaches described above. The basic intent of the study is to develop a tool for the analysis of alternative emission control strategies, which allows

- the determination of international cost-efficient allocations of reductions of acidic emissions,

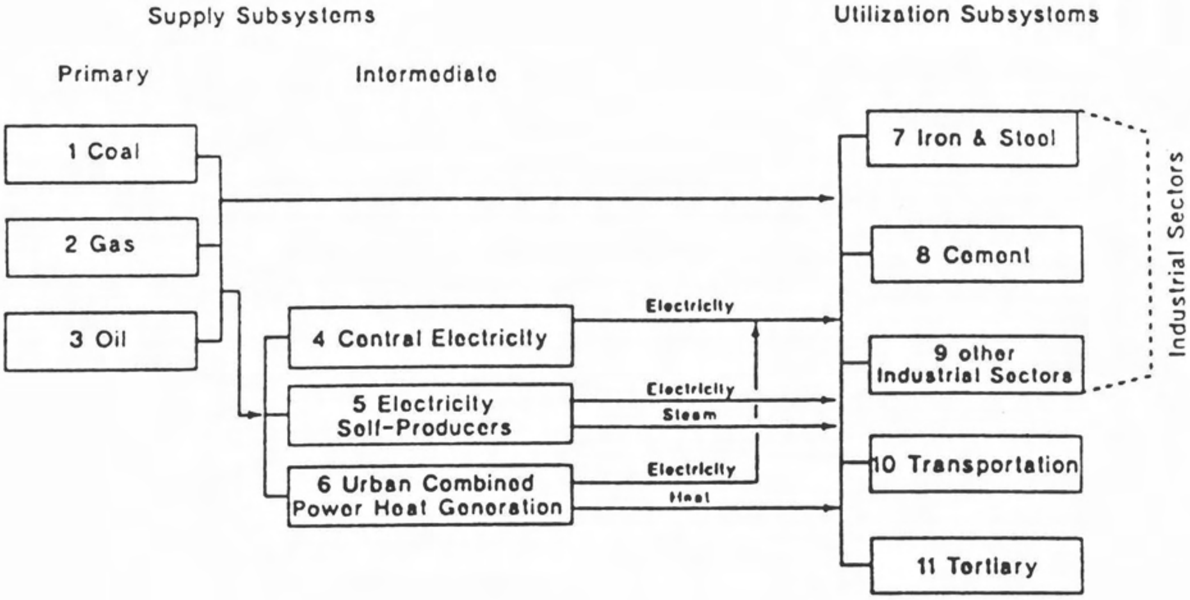

Figure 1: The modular structure of the EFOM-ENV model

- considering the full range of available emission control options also including structural changes in the energy systems,
- with special emphasis on the analysis of the combined reductions of several pollutants (in particular SO_2, NO_x and CO_2), exploring the cost saving potential of control measures affecting the emissions of several substances.

The remainder of the paper is organized as follows: in the second section, the current status of model development is briefly reviewed both for the IIASA-RAINS and the EC-EFOM-ENV models. The third chapter describes the methodology developed for the linkage of these two models. In the fourth section a comparison of model results for the sample case – the Federal Republic of Germany – is provided.

2 Current status of model development

2.1 The EFOM-ENV model

The energy-emission model EFOM-ENV is a linear dynamic optimization model. It is driven by an exogenously specified demand for useful or final energy. The characteristics and interrelations of the energy flow (from the primary energy supply, through the intermediate conversion stages, e.g. electricity generation, to the final demand sectors such as industry, households,

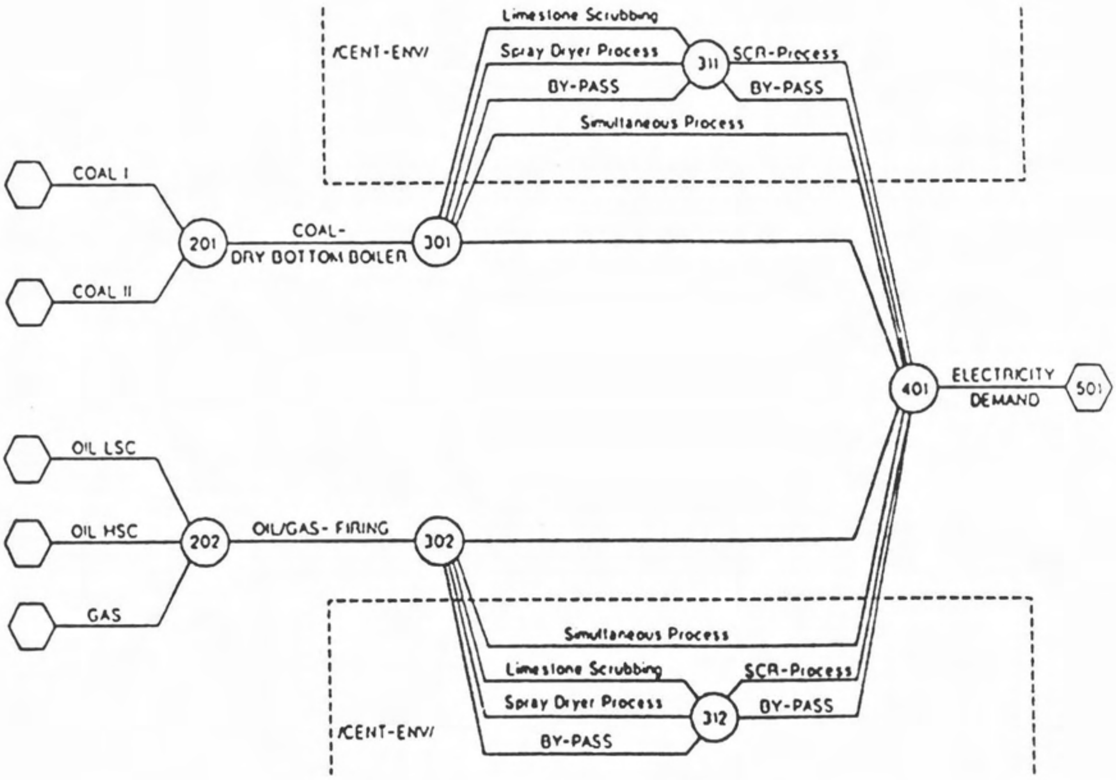

Figure 2: Simplified structure of an environmental module in EFOM-ENV

transportation etc.) are described by linear equations. Figure 1 shows the structure of the model, which is organized in a modular way with each module or sub-system containing a set of alternative energy conversion techniques. These techniques are described according to their technical characteristics (conversion efficiencies, installed capacities, by-products etc.) as well as by their economic (investments, operating costs) and environmental (emission factors for several substances) properties [4], [11].

The optimization routine identifies cost optimal system configurations over a period of time that satisfy both the exogenously specified final/useful energy demand and a variety of other user-determined peripheral constraints. In particular, environmental regulations can be expressed as such peripheral constraints in several ways:

- The total amount of emissions in individual subsystems or in the entire energy system can be restricted.
- Only those techniques that adhere to certain technological standards (e.g. in terms of emissions etc.) are allowed to operate.
- The use of certain fuel types (e.g. those with high sulfur content) can be restricted.

As mentioned above, a large number of available energy conversion techniques are represented in the model from which the cost-minimal combination is determined through the optimization procedure. In addition to existing energy conversion processes future high-efficiency low-emission techniques (e.g. fluidized bed combustion or combined cycle processes with integrated coal gasification for electricity production), which might become available by the end of this century, are also included.

The original purely energy oriented model has been extended with an "environmental" module, describing the variety of currently available and anticipated emission control technologies (Figure 2, Tables 1, 2).

Consequently, at the moment the following basic options for emission reductions are taken into consideration by EFOM-ENV:

- emission reduction techniques (as listed in Tables 1, 2),
- fuel switching and improvement of fuel quality,
- technology substitution, i.e. use of less-emitting combustion techniques,
- energy conservation and efficiency improvements.

Recently the EFOM-ENV model has been extended by an energy conservation module, featuring

- improved insulation for buildings,
- more efficient household appliances (gas and electric cookers, refrigerators, washing machines etc.),
- lower electricity consumption for lighting (all in the tertiary/domestic sector), and
- improved fuel efficiencies for cars, trucks, railways, aircrafts and buses.

EFOM-ENV is currently in use for all Member States of the European Community as well as for Finland and Turkey with the aim of developing cost-efficient emission reduction strategies. These analyses are carried out by the IIP of the University of Karlsruhe in close collaboration with the Commission of the European Committee (CEC) and research institutes in the related countries [4], [10], [11], [12]. The IIP will apply the model to other non-EC countries in the next few years, e.g. Hungary, Lithuania, Russia.

Table 1: Set of SO_2 control measures included in the EFOM-ENV model

Sectors	Technology	Set of measures
Central Conversion	Coal/oil/gas	WLP, FSw
	Oil-Gas	WLP, FSw
	Oil-fired	WLP, FSw
	Con-CCPP	WLP, FSw
	Lign-DBB	WLP, FSw
	Coal-DBB	WLP, FSw
	Coal-WBB	WLP, FSw
Industrial Power Plants	Coal/oil/gas	WLP/SDP, DSI, FSw
	Lignite-DBB	WLP/SDP, DSI, FSw
	Grate-fire	WLP/SDP, DSI, FSw
	BPT	WLP/SDP, DSI, FSw
	ECT	WLP/SDP, DSI, FSw
Heating Plants	Coal/oil/gas	WLP, DSI, FSw
	Con-CCPP	WLP, FSw
	ECT	WLP, DSI, FSw
	BPT	WLP, DSI, FSw
	Incinerator	WLP, DSI
Industry	Blastfurnace	WLP, FSw
	Boiler	WLP, FSw
	Refinery	SDP, Act. Carbon, FSw
Tert./Dom. Sector		Flue gas washing systems

Abbreviations:

BPT	Back pressure turbine
BPS	Block power station
Cat	Three-way catalyst
Con-CCPP	Electricity generation using conventional combined cycle power plants
DBB	Dry bottom boiler
DSI	Dry sorbent injection
ECT	Extraction condensing turbine
EGR	Exhaust gas recirculation
FSw	Fuel switching
PM	Primary measures
SCR	Selective catalytic reduction
SDP	Spray dryer process
WBB	Wet bottom boiler
WLP	Wet limestone process

Table 2: Set of NO_x control measures considered in the EFOM-ENV model. (The abbreviations used are listed below Table 1.)

Sector	Technology	Set of measures
Central Conversion	Gas-fired	PM, SCR
	Gas-Turbine	PM, SCR
	Coal/oil/gas	PM, SCR, FSw
	Oil-Gas	PM, SCR, FSw
	Oil-fired	PM, SCR, FSw
	Con-CCPP	PM, SCR, FSw
	Lignite-DBB	PM, SCR
	Coal-DBB	PM, SCR, FSw
	Coal-WBB	PM, SCR, FSw
	IG-CCPP	SCR, FSw
Industrial Power Plants	Coal/oil/gas	PM, SCR, FSw
	Lignite-DBB	PM
	Grate-Fired	PM, FSw
	BPT	PM, SCR, FSw
	ECT	PM, SCR, FSw
	Gas-Turbine	PM, SCR
	BPS	SCR
Heating Plants	Coal/oil/gas	PM, SCR, FSw
	Gas-Turbine	PM, SCR
	Con-CCPP	PM, SCR, FSw
	ECT	PM, SCR, FSw
	BPT	PM, SCR, FSw
	BPS	SCR
	Incinerator	PM
Industry	Blastfurnace	PM, SCR, FSw
	Roll-Mill	PM
	Boilers	PM, SCR, FSw
	Refinery	SCR, Act. Carbon, FSw
Tert./Dom. Sector		Yellow flame burner
		Blue flame burner
Transport Sector	Cars 1.0 l	Cat
	Cars 1.4 l	EGR, Cat
	Cars 2.0 l	EGR, Cat

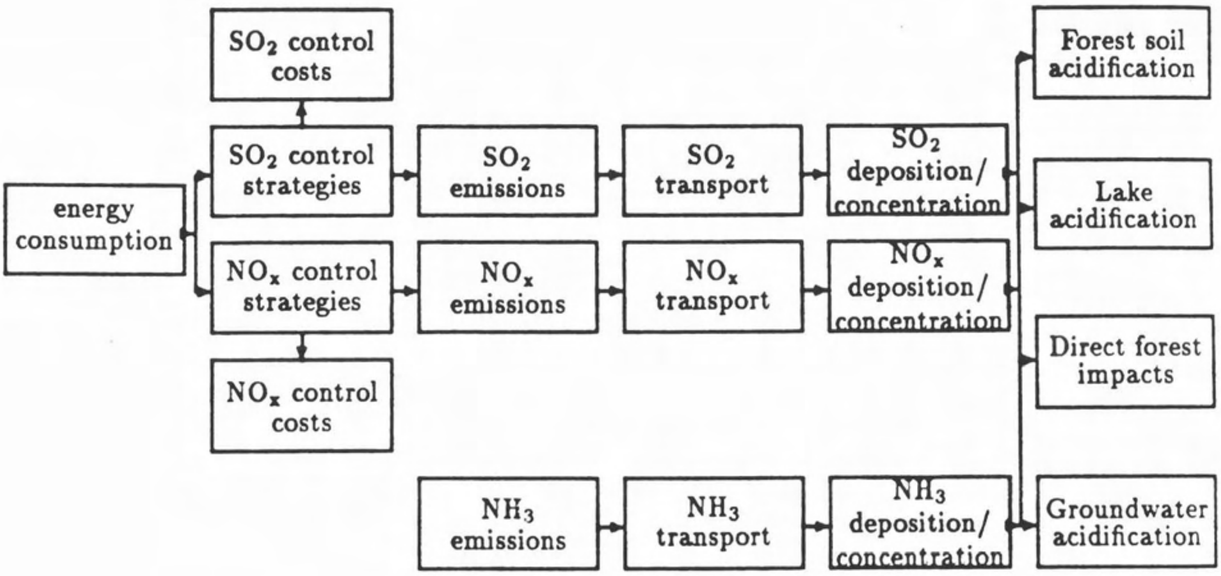

Figure 3: Simplified structure of the RAINS model

2.2 The RAINS model

The Regional Acidification Information and Simulation (RAINS) model developed at IIASA simulates the transboundary flow of acidifying air pollutants from the sources of emissions to their regional impacts on different ecosystems in Europe (Figure 3). Based on energy consumption statistics and user-defined control strategies, emissions of SO_2, NO_x and NH_3 are computed for all 27 European countries. The transboundary transport of these pollutants is calculated based on results of the European Monitoring and Evaluation Project (EMEP) in order to predict acid deposition on a spatial resolution of a 150x150 km grid over the entire Europe and Continent. Environmental impacts of acid deposition are simulated for forest soils and freshwater bodies; for forest ecosystems the effects of elevated SO_2 concentration are simulated on a regional scale.

The model can be operated in two ways: Given a certain pattern of energy use, it can estimate geographical patterns of sulphur and nitrogen deposition, the effects upon certain aspects of the environment, and the costs of selected abatement measures. Alternatively the model can indicate the optimal allocation of emission reductions, given a set of regional deposition limits.

Because of the broad geographical scope of the model the level of resolution that can be maintained by RAINS is lower than in models that focus only on a single country. This applies not only to spatial disaggregation of the simulation of environmental impacts, but also to the assessment of emissions and pollution control costs, which is based on aggregated energy consumption data. Whereas the computation of sectoral and national emission figures is not hindered by this restriction, the analysis of emission control strategies within RAINS is limited to technical "add-on" abatement options. The major emission reduction measures currently considered by the RAINS-model for SO_2 are:

- Use of fuels with lower sulfur content (low sulfur oil and coal),
- desulfurization of fuel oil,
- SO_2 reduction during the combustion process (e.g. by the limestone injection process),
- desulfurization of the flue gases (e.g. by the wet limestone flue gas desulfurization process), and
- high efficient regenerative techniques (e.g. the Wellman-Lord process).

For NO_x reduction, the control options distinguished in the RAINS model are:

- Combustion modification (primary measures) and
- the "Selective Catalytic Reduction" (SCR) process for stationary sources;
- the uncontrolled catalyst and the
- controlled three-way catalyst for four-stroke gasoline cars;

and

- the introduction of the U.S. Norm 1985 and the
- U.S. Norm 1991 for heavy duty diesel trucks.

These emission control options are applicable to prespecified patterns of energy consumption determined exogenously by the model user. Therefore, the economic aspects of emission reductions achieved through structural changes of the energy system (the most important are fuel and technology substitution processes and energy conservation measures) can not be evaluated by the current model version, because not all structural data necessary for a complete analysis are available within RAINS.

At the moment, the RAINS model is being extended with a module for the assessment of the reduction potential and the control cost of ammonia emissions in Europe that are mainly a result of agricultural activities.

3 The model linkage: Methodology

A linkage between these two types of model can be established in the form of "national cost curves" for emission reductions. Such cost curves denote the minimal-cost combinations of the available emission control measures for varying levels of overall national emission reductions. These cost curves can be constructed by each of the two models. Consequently, a model linkage can substitute cost curves derived within integrated assessment models for the more comprehensive representation of energy-emission models. These modified cost curves can then be used by integrated assessment models for further analysis, such as the international optimization of emission reduction measures for the attainment of prespecified regional deposition levels.

3.1 National cost curves implemented in the RAINS model

The derivation of such cost curves is implemented on a routine basis in the RAINS model by ranking the abatement options according to their marginal cost efficiencies [2]. The costs of emission reductions are expressed as the annual cost necessary to maintain an emission level assuming a constant pattern of energy consumption. Therefore, investments are annualized over the lifetime of the equipment. The resulting annuities together with the annual fixed and variable operating costs constitute the total annual cost of emission reductions.

This formulation, as it is implemented in the RAINS model, represents a static approach, ignoring potential dynamic effects such as uneven age structures of plants, varying capacity utilizations, limited market penetration rates of new technologies etc. In order to limit possible inaccuracies introduced by this simplification, the time horizon of the current version of the Energy/Emission/Cost module of the RAINS model currently ends with the year 2000. However, this static approach allows a considerable simplification of the model implementation in terms of computer power and data requirements, which has to be judged in the light of the limited availability and reliability of data on an international level.

3.2 The derivation of national cost curves with the EFOM-ENV model

In contrast to this static scheme, the EFOM-ENV model applies a quasi-dynamic approach. Instead of considering the situation at one point in time only the model analyzes the temporal development of the energy system over a planning horizon of several decades. This planning period is divided into subperiods, generally of five years length, of which each first year is modeled as a reference year for the entire period. The EFOM-ENV approach thereby takes explicit account of the age structure of the existing plants, the dynamics of market penetration of innovative technologies and the time structure of emission control regulations. The intertemporal optimization approach balances the resulting dynamics of the energy supply system with the evolution of energy demand. This dynamic perspective may have special relevance for the development of emission control strategies, since limited substitution rates caused by the long life of equipment in the energy sector may place serious constraints on the temporal feasibility of future emission reduction strategies.

Consequently, EFOM-ENV provides the optimal *inter-temporal* allocation of resources, combustion technologies and emission control methods for the selected optimization criterion. By default the objective function of the optimization follows the "cost-approach". The objective function represents the present value of total energy system costs over time, i.e. the total cost of the energy system, discounted on January 1 of the base year 1980 and accumulated up to the horizon year [15]. It is composed of variable cost coefficients (proportional to energy or material flows) as well as of fixed cost and capital cost (both proportional to the newly invested capacity).

In order to attain compatibility with the static approach as it is implemented in the RAINS model it is necessary to report abatement costs on an annual level. This information is not provided by EFOM-ENV on a routine basis; therefore, a special software routine has been developed to extract this information from the individual optimization results.

Based on this procedure, the national cost curves were derived as follows:

1. Assuming an exogenously specified energy demand structure the model was operated given different levels of national emission reductions.

2. National emission levels were gradually reduced from the "doing nothing-case" (the "Reference Scenario") down to the level of maximum feasible emission reductions and used as constraints for the cost optimization. This optimization identifies the optimal system configuration for each emission level.

3. The costs of these emission control scenarios have been compared with the cost of the Reference Scenario, in which no emission reduction is required.

In this way, emission control costs are defined as the increase of the total annual cost of the energy system for the emission control scenario relative to the Reference Scenario. In an analogous manner the emission control measures can be identified as the changes in the mix of energy conversion and emission control technologies relative to the Reference Scenario.

4 A comparison of national cost curves for West Germany

In this section cost curves derived by the EFOM-ENV model will be compared to results from the RAINS model. The comparisons are carried out for energy consumption in the former area of the Federal Republic of Germany, which will be referred to in the following as "West Germany".

4.1 The Reference Scenario

The methodology used to derive national cost curves with the EFOM-ENV model as outlined above requires the definition of a hypothetical Reference Scenario, against which changes caused by imposed emission reductions can be compared. For the sake of comparison such a scenario has been developed with the help of EFOM-ENV, in which – for methodological reasons – no emission controls for SO_2, NO_x and CO_2 are required. Consequently, it is assumed in the Reference Scenario that no emission control measures are taken after 1980, thus extrapolating the status-quo of the emission standards of 1980 up to the end of the century. For the same reason also all energy conservation measures are excluded from consideration. This means that measures, which in reality have been already taken since 1980, are neglected. Therefore, all emission control costs and measures in this paper refer to this "doing-nothing-case", rather than to the actual energy pathway.

4.1.1 Assumptions made in the Reference Scenario

The development of the energy demand between 1980 and 1985 is extracted from the EUROSTAT statistics [5]. The evolution of the future demand is based upon the projections of the Commission of the European Community (CEC) [7]. Apart from the underlying demand projection, the Reference Scenario includes a set of assumptions on general economic parameters, which are amongst others (see [4], [11]):

- a 2.8 % annual growth rate of the GDP,
- a steady increase in the crude oil price from $ 17 per barrel in 1990 to $35 in 2000 (in current dollars),
- a parallel development of the world market prices of natural gas and coal,
- and a real interest rate of 4% per year.

Identical assumptions are likewise used in the emission reduction scenarios.

4.1.2 The aggregated energy balance of the Reference Scenario

The sectoral energy consumption of the Reference Scenario for the year 2000 is shown in Table 3, using the classification applied in the RAINS model. It should be emphasized once more that this energy balance is the outcome of an optimization of the energy development for Germany, rather than a forecast. It is hypothetical in the sense, that no emission control measures are required and consequently they are not implemented by the cost minimization procedure unless they result in the lower overall cost of the system.

Table 3: Energy Use by Sectors in 2000 (PJ) of the EFOM-ENV Reference Scenario

Fuels	Energy conv.	Power plants old - new	Ind. sector	Non-energ. use	Dom. sector	Transp.
LIgnite	0	645 - 40	105	0	0	0
Hard Coal	185	875 - 874[a]	189	0	61	0
Deriv. Coal	0	0	395	58	13	0
Other Solids	0	9 - 49	0	0	1	0
Hvy Fuel Oil	50	0	20	338[b]	33	0
Middle Dist.	1	0	74	68	1029	650
Light Frac.	0	0	0	299	0	1231
Gas	254[c]	410 - 46	824	90	893	0
Nuclear	0	695 -1133	0	0	0	0
Hydro	0	70 - 5	0	0	0	0
Electricity	34	-1584	763	0	739	48
Distr. Heat	0	-159	117[d]		42	0

[a]WBB: 338 (81) PJ old (new) plants, DBB: 285 (445) PJ old (new) plants

[b]Including bitumen, lubricants, petroleum coke

[c]Transport losses: 149

[d]Steam

Table 4: Energy Use by Sectors in 2000 (PJ) of the RAINS Official Energy Pathway

Fuels	Energy conv.	Power plants old - new	Ind. sector	Non-energ. use	Dom. sector	Transp.
Lignite	0	913 - 97	53	0	0	0
Hard Coal	93	1302 - 127[a]	119	0	27	0
Deriv. Coal	0	0	435	0	46	0
Other Solids	0	105	29	0	12	0
Hvy Fuel Oil	97	157	243	0	0	0
Middle Dist.	0	6	157	0	1159	659
Light Frac.	0	0	85	0	0	1290
Gas	141	250 - 24	666	99	865	0
Nuclear	0	1582	0	0	0	0
Hydro	0	179	0	0	0	0
Electricity	193	-1660	721	0	714	41
Distr. Heat	31	-230	32	0	167	0

[a]WBB: 782 PJ old plants, DBB: 521 (127) PJ old (new) plants

Since the EFOM-ENV model contains a much higher degree of structural detail, energy consumption data must be aggregated to match the RAINS data base format. The following rules have been applied to derive consistency:

- The RAINS "energy conversion" sector in Table 3 aggregates the coal, oil and gas subsystems of the EFOM-ENV model;
- The RAINS "power plants" sector encompasses the EFOM-ENV "central electricity generation", "industrial autoproducers", "urban heat" and "power co-generation" activities.
- The cement, iron and steel and "miscellaneous industries" subsystems of the EFOM-ENV model are aggregated under the RAINS "industry" sector.
- "Hard Coal" as defined by RAINS comprises the two different qualities of steam coal and metallurgical coal, as they are distinguished in the EFOM-ENV model.
- The RAINS "Derived Coal" deposition represents coke and briquettes.
- "Other Solids" includes the EFOM-categories wood, peat, biomass and refuse.
- The EFOM-ENV fuel categories low-sulfur and high-sulfur fuel oil, bitumens, lubricants and petroleum coke are classified by RAINS as 'Heavy Fuel Oil'.
- Light heating oil and diesel oil are counted as "Middle Distillates".
- Gasoline, kerosene, jet fuel and naphta represent the "Light Fractions" in RAINS.
- The RAINS category "Gas" contains natural gas for energy and non-energy use, town gas, LPG, as well as secondary gases, i.e. refinery gas, cokery gas and blast-furnace gas, which are counted as separate fuel types in the EFOM-ENV model.
- Nuclear energy and hydropower is expressed by the thermal equivalent of electricity production.

4.2 The cost curves for the Reference Scenario

For the energy consumption pattern of the year 2000 as it has been derived for the Reference Scenario the cost curves for control of SO_2 and NO_x emissions as computed with the RAINS model will be compared to results of the EFOM-ENV computations.

The comparison of the SO_2 cost curves shows the RAINS estimates to always be higher by an almost constant margin of some 0.4 billion DM/year over the entire range of emission reductions (Figure 4). With the exception of this constant margin the differences between these curves are minor. An analysis of the sequence of abatement measures taken by the two models reveals the major reason for the lower cost estimate of the EFOM-ENV model: As displayed in Figure 6, the systems approach of the EFOM-ENV model options uses some technology and fuel substitution first as the cheapest emission control options in order to reduce the first 10 percent of SO_2 emissions. In contrast to this, the RAINS-approach is fixed to the prespecified energy consumption of the Reference Scenario and therefore has to abate this initial 10 percent by emission control technologies (flue gas desulfurization) at higher cost (Figure 7). According to Figure 4, these cost savings of the EFOM-ENV case amount to roughly 0.4 billion DM/year.

After this inexpensive potential provided by structural changes is exhausted, the sequence of actions is rather similar in both cases. A minor difference occurs in that the RAINS model applies flue gas desulfurization for lignite fueled power stations already at lower reduction levels than EFOM-ENV is selecting it, whereas EFOM-ENV uses first the full potential of desulfurization of hard coal power stations. This can be explained by the fact, that the RAINS model assumes higher investments for the retrofit case, making the installation at newly built stations cheaper.

For NO_x control, the curves exhibit a rather close match up to a reduction level of some 40 percent (Figure 5). For further reductions, EFOM-ENV estimates sharply increasing costs, whereas the RAINS model projects relatively modest growth. Several aspects should be mentioned:

- Whereas the levels of unabated emissions (in the Reference Scenario) are almost identical, the RAINS model estimates a maximum emission reduction level of about 70 percent, whereas EFOM-ENV leads only to a maximum reduction of 60 percent.

- This difference is mainly caused by the different sets of control measures for mobile sources considered in the models. Both models describe several options for NO_x reduction from gasoline engines; for heavy duty diesel trucks, at present no emission controls are foreseen in the EFOM-ENV model, whereas the RAINS model allows up to 40 percent reduction the introduction of the U.S.Norm 1991. Therefore, this additional reduction potential increases the maximum feasible reductions in the RAINS model by some 10 percent.

- Although EFOM-ENV takes account of technology and fuel substitution as a means for emission reductions, in the case of NO_x reduction such measures are only selected for high reduction levels, resulting in sharply increasing overall cost at the end of the cost curve. This is in contrast to SO_2 reductions, where such structural changes represent an inexpensive control potential.

- As displayed in Figures 8 and 9, the sequence of actions is almost identical as far as stationary sources are concerned, resulting in similar abatement cost estimates up to a reduction level of 50 percent.

- The cost increase beyond the 50 percent level as it occurs in the EFOM-ENV results is caused

  (a) by different assumptions about the cost of the controlled three-way catalysts for gasoline cars and

  (b) by the high costs of restructurization, whereas the additional NO_x reduction measures assumed in RAINS allow the same reduction levels at lower cost.

This analysis shows that, as long as structural changes are excluded from consideration, the two models provide consistent results. Differences can be traced back to different assumptions made in each of these models.

5 Cost curves for different energy scenarios

Emission reduction costs are sensitive to changes in fuel consumption. The following is a detailed explanation of this dependency.

As previously mentioned the Reference Scenario (Table 3) may be regarded as one of the possible future developments of the West German energy system. The particular characteristic of this scenario, which distinguishes it from the manifold other scenarios is its cost optimality, obtained as a result of the optimization approach implemented in EFOM-ENV. Other scenarios exist and may have different properties.

Different characteristics of alternative scenarios, however, also occur in relation to their emission reduction cost. In this section the cost curves derived for the Reference Scenario will be compared to three other examples:

- In contrast to the Reference Scenario, which represents an optimized strategy, the official energy projection for the year 2000 as it is published in [8] is adopted as a base (Table 4). The related cost curves have been derived by the RAINS model.

- In the second example the EFOM-ENV model is used to explore the potential of energy conservation for the purpose of emission reductions. Based on identical assumptions for the development of final/useful energy demand as in the Reference Scenario, this scenario makes use of all energy conservation options provided in the current EFOM-ENV implementation as they are listed in Section 2.1.

- In the third case structural changes (fuel substitution) are intentionally utilized to achieve cost efficient emission reductions. Again, this can be explored with the help of the EFOM-

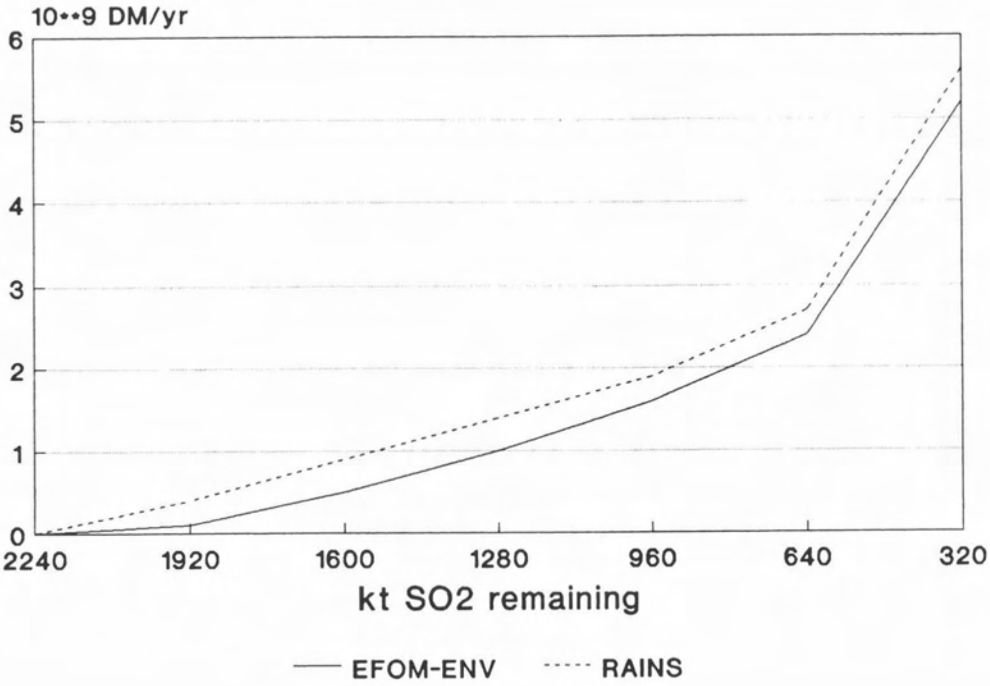

Figure 4: Comparison of the national cost curves for SO_2 reduction based on the energy consumption of the Reference Scenario for the year 2000.

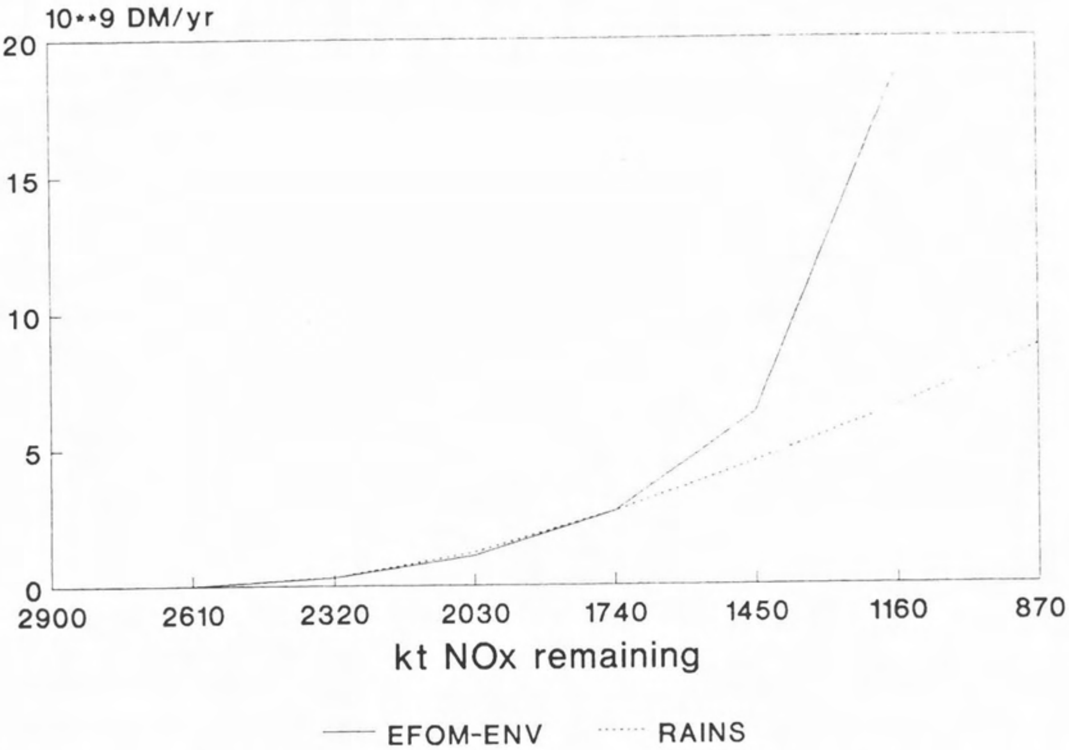

Figure 5: Comparison of the national cost curves for NO_x reduction based on the energy consumption of the Reference Scenario for the year 2000.

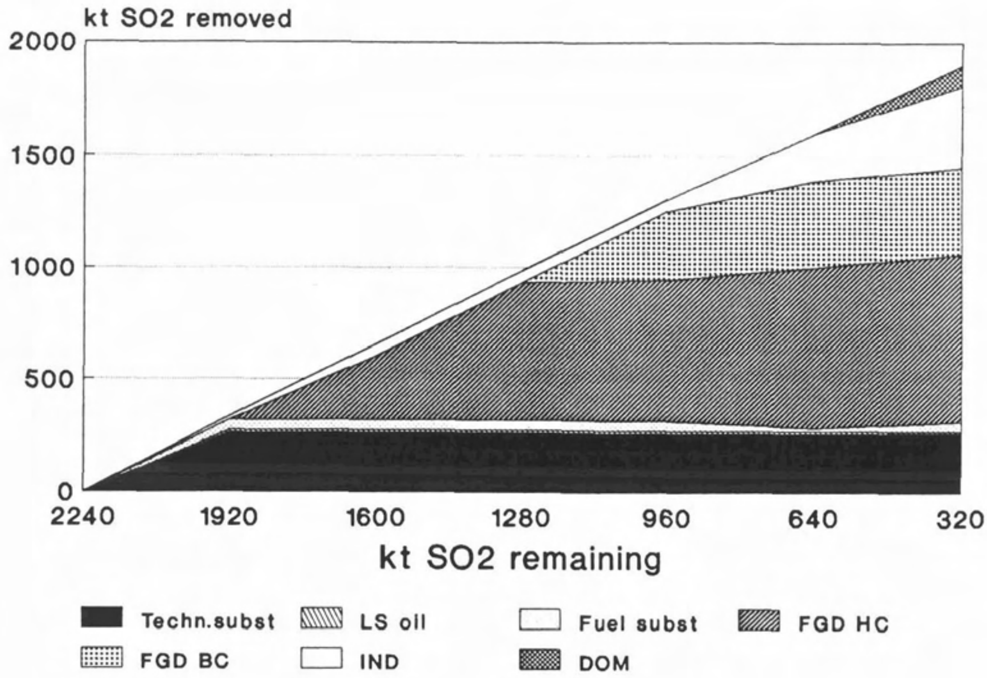

Figure 6: SO_2 reductions achieved by different control options for the Reference Scenario in the year 2000 – Results of the EFOM-ENV model

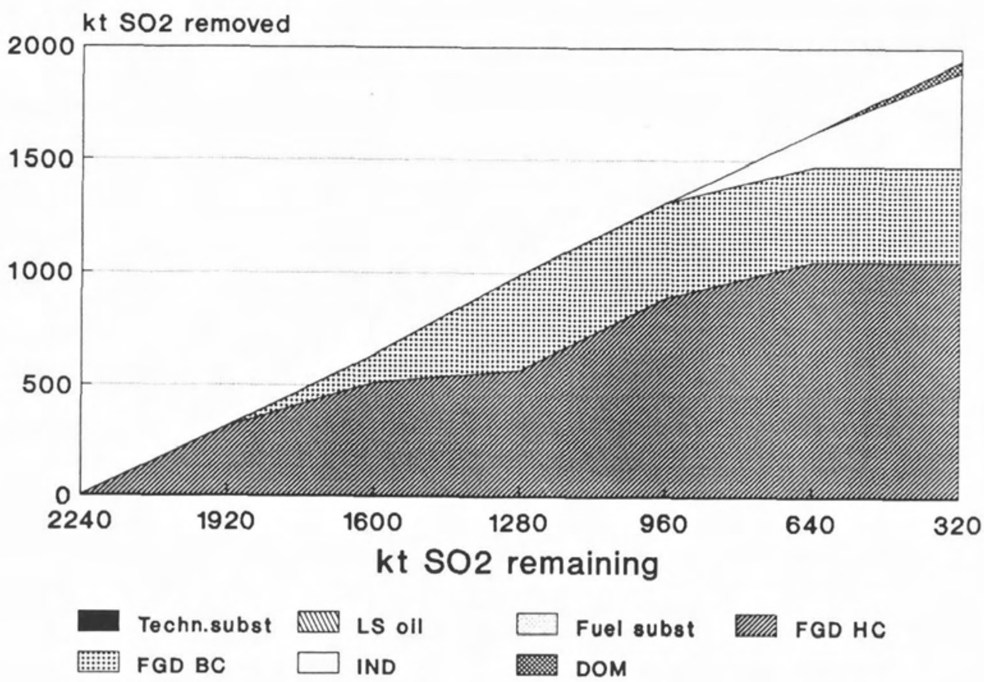

Figure 7: SO_2 reductions achieved by different control options for the Reference Scenario in the year 2000 – Results of the RAINS model

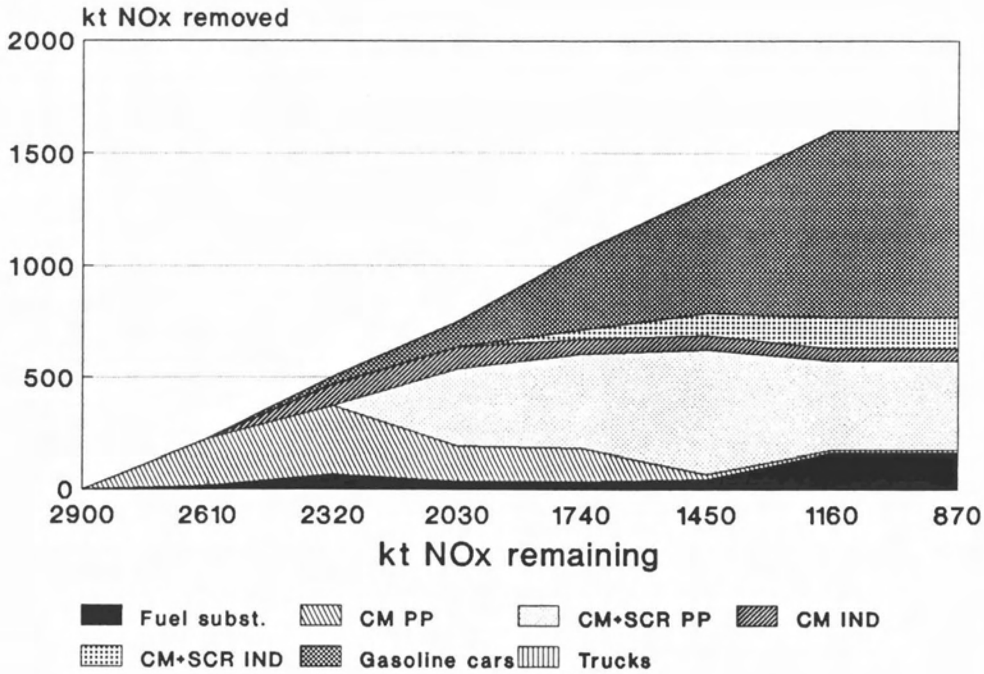

Figure 8: NO_x reductions achieved by different control options for the Reference Scenario in the year 2000 – Results of the EFOM-ENV model

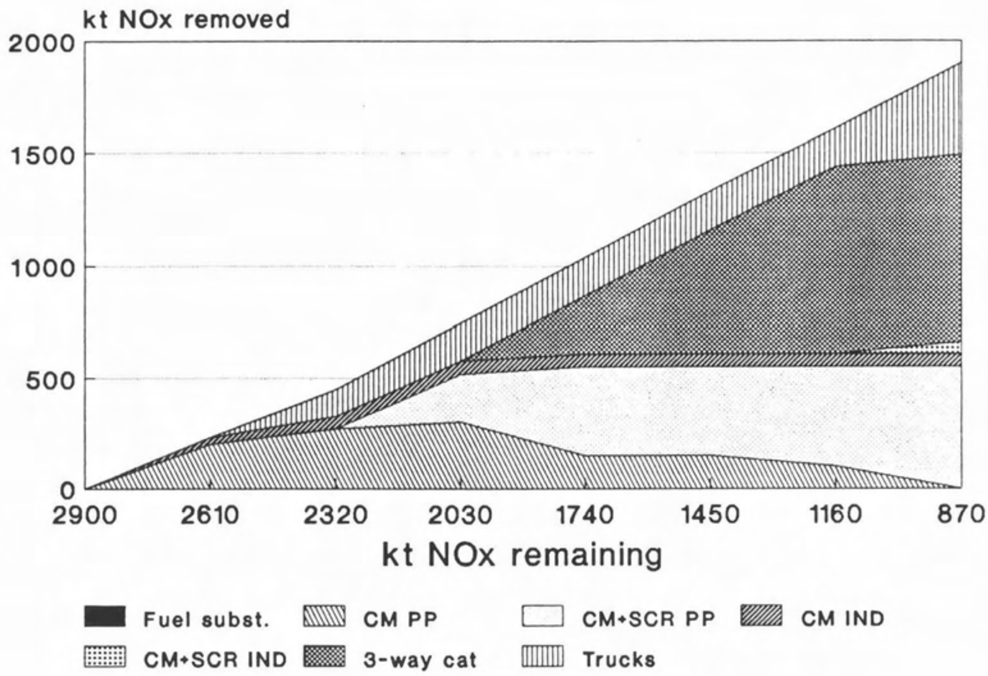

Figure 9: NO_x reductions achieved by different control options for the Reference Scenario in the year 2000 – Results of the RAINS model

ENV model if additional options for fuel substitution (e.g. ignoring the current commitments enforcing the use of domestic hard coal as specified in the German contract between hard coal mining industries and electricity generating companies) are provided.

The differences in the cost curves are displayed in Figure 10.

The effect of the cost minimization is already evident for the unabated emission level of the Reference Scenario (2240 kt SO_2), for which emissions controls would already be necessary in the case of the officially projected energy consumption pattern. This means that the general cost minimization approach, even in the absence of emission constraints – at least in this case – results in lower SO_2 and NO_x emissions. Furthermore, abatement cost for the non-optimized scenario increase faster than in the optimized case.

Energy conservation measures may contribute to a cost decrease for emission reductions. In our example, however, this effect is not very distinct. This is due to the short time period provided in the model calculations for the restructuring (only up to the year 2000). It should be mentioned that analyses with a longer time horizon result in considerably higher cost savings: For example, an analysis carried out for the long-term development of Turkey indicated a cost saving potential of 25 percent if a time horizon of 40 years is considered [10].

Substantial cost savings can be achieved by means of fuel substitution. The third case demonstrates, that fuel substitution allows SO_2 reductions of 80 percent (compared to 1980) at the same cost as the Reference Scenario, in which SO_2 emissions decline by only 30 percent.

As displayed in Figure 11, similar effects occur for NO_x abatement cost, which are not discussed here in full detail. Again, the RAINS case is not fully comparable because different assumptions on availability and cost of control measures for the mobile sector were made.

6 Simultaneous emission reductions for several pollutants

Whereas the RAINS model in its current form is only able to analyze emission control costs for several pollutants individually, the systems approach of EFOM-ENV allows consideration of the interrelations which exist between emission control measures for different pollutants. Though the reduction of SO_2 through abatement technologies does not affect NO_x emissions substantially, and vice versa, energy-related control measures, i.e. fuel switching and technology substitution, may affect both pollutants. One example is the switching from coal to gas which reduces SO_2 and NO_x at once. Thus there may be cost saving potential if several pollutants are considered in combination [1].

[1]However, the combined reduction does not necessarily result in cost savings: There are emission control measures, which tend to increase other pollutants. For example, the substitution of the dry process by the wet process for cement production, chosen for NO_x reduction, increases the energy consumption and thus tends to

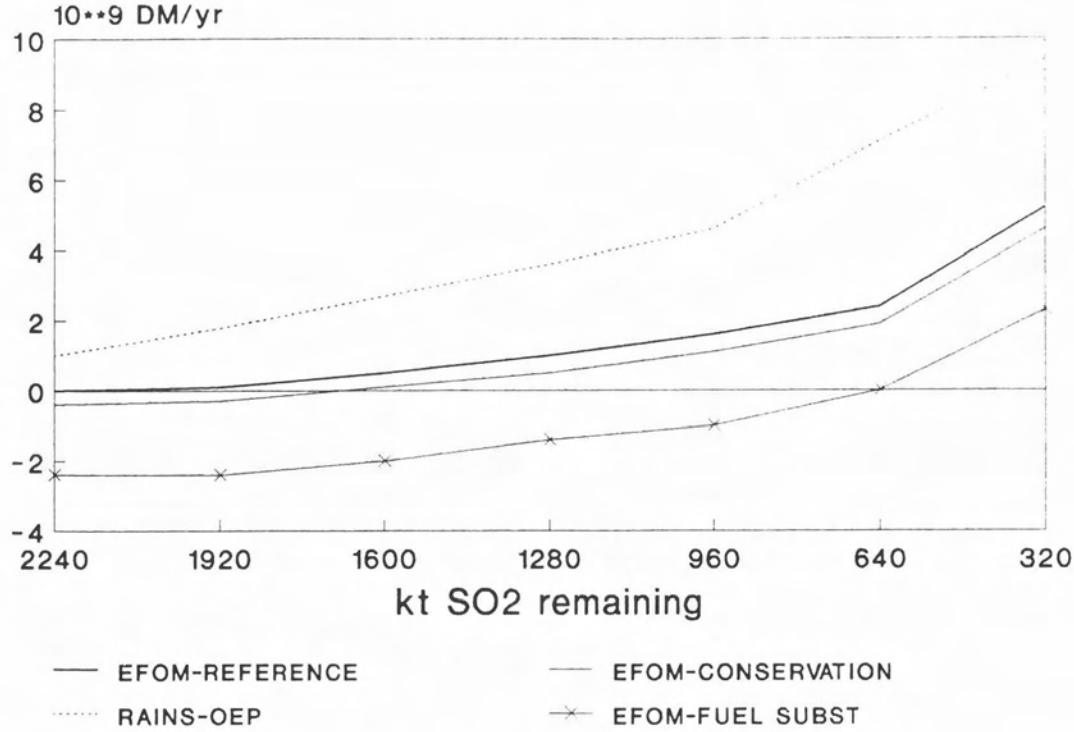

Figure 10: Comparison of cost curves for SO_2 reductions

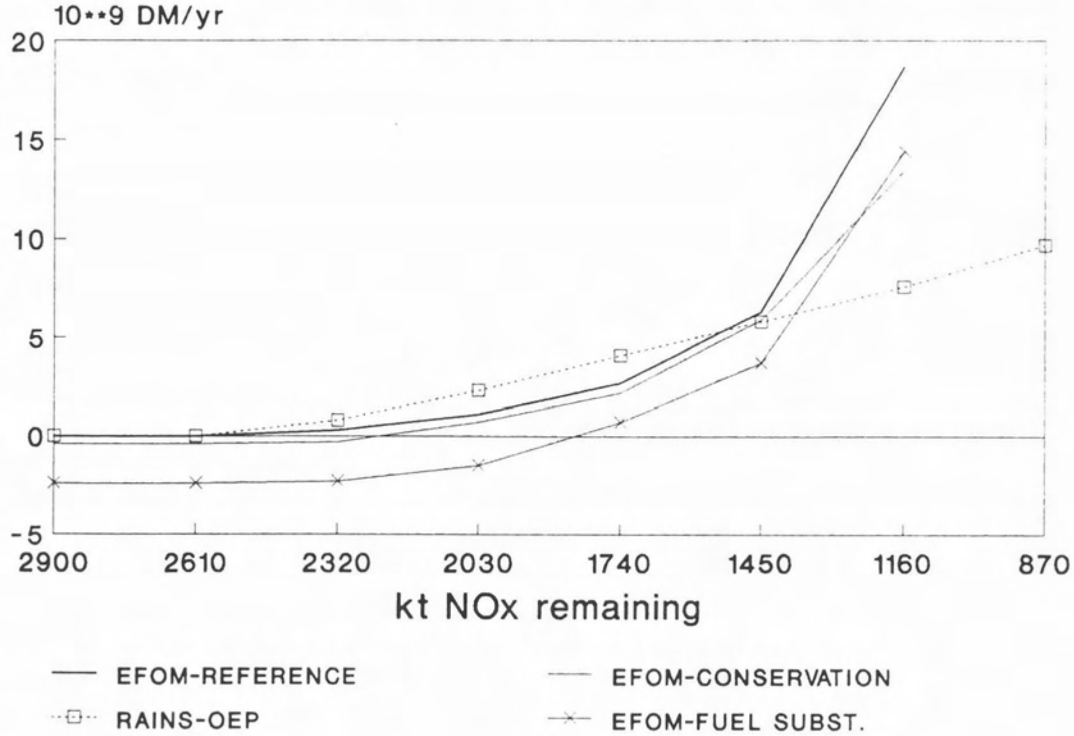

Figure 11: Comparison of cost curves for NO_x reductions

Figure 12 shows an example for West Germany: In the case of a fixed 60% SO_2 reduction, a simultaneous consideration of additional NO_x reduction measures could save between 0.2 and 0.8 billion DM/year compared to separate reductions of both pollutants. Still, this cost saving potential is only about 1% of total abatement costs. If, in addition, the German coal contract is lifted (the 'EFOM-Fuel Substitution' case), a cost saving of 4% can be reached, basically by increasing the production of electricity from natural gas while reducing the production from coal fueled power stations.

Although in the analyzed cases the cost saving potentials are small compared to total abatement costs, it shows nevertheless, that an increased flexibility in the energy system (as obtained in the above mentioned example by lifting the coal contract) will provide additional emission control options and hence a potential for cost savings. Due to the fact that in this preliminary analysis only the period up to the year 2000 has been considered with a rather low increase in energy demand, only very limited freedom exists for adaptations in the structure of the West German energy supply system. Therefore, the potential for technology substitution, which can be applied for the combined reduction of SO_2 and NO_x is low, given the coal contract and other energy policy constraints. It has been demonstrated that in countries with highly dynamic energy systems, or for studies with an extended time horizon due to the increased flexibility of the systems considerably higher cost saving potentials also exist [10].

7 Integration of CO_2 reduction strategies

Energy strategies are currently being reviewed for their potential to reduce CO_2 emissions in order to delay global climate change caused by greenhouse gases. When developing emission control strategies it seems advisable to consider required emission reductions for all pollutants simultaneously in order to identify possibilities for cost efficient solutions. Again, such analyses depend crucially on the ability to consider structural changes as means for emission reductions. Energy-emission models such as EFOM-ENV provide these capabilities and will therefore be used in this section to explore the interrelation of SO_2 and NO_x emissions.

As a first step, the SO_2 and NO_x reduction strategies introduced in this paper are analyzed with regard to their CO_2 emissions. Figure 13 shows that for these scenarios CO_2 emissions decline slightly with increasing levels of SO_2 resp. NO_x reductions. This is a result of the fuel and technology substitutions applied in order to reduce acidic emissions. If energy conservation and fuel substitution measures are included as emission control options, larger CO_2 reductions occur. However, it must be stated that the magnitude of CO_2 reductions are rather small. Since

increase SO_2. In such cases, RAINS "individual approach" results in an under-estimation of the emission control costs.

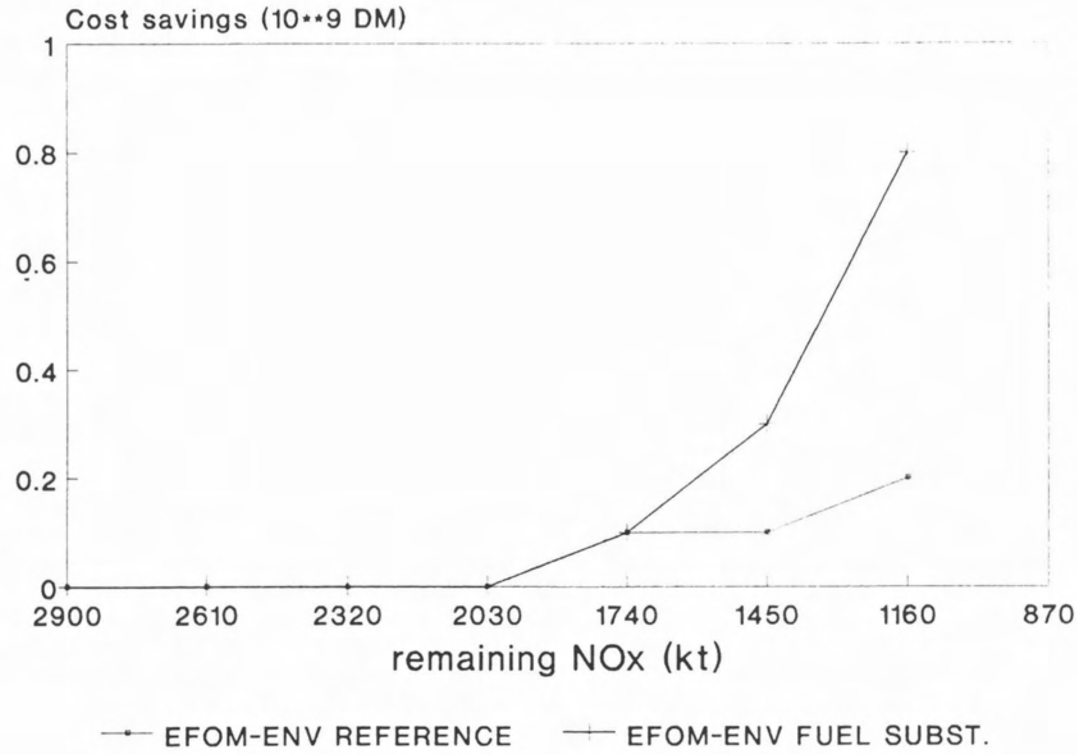

Figure 12: Cost savings of combined NO_x reduction at a 60 % SO_2 reduction level

the larger part of SO_2 resp. NO_x reductions is achieved by emission control technologies, only limited changes have been applied to the basic energy consumption structure.

If, on the other hand, an emission constraint is put on total CO_2 emissions, then significant reductions also occur for SO_2 and NO_x as a side effect. Preliminary results of a study on the reduction of greenhouse gas emissions, which is currently carried out by the Commission of the European Community, the IIP and other institutes within the EC, indicate that for example a 30 % reduction of CO_2 emissions in West Germany in the year 2010, which is currently stated as the policy target, will also reduce SO_2 emissions by 43 % compared to the Reference Case. Unabated NO_x emissions would be 18 percent lower (Figure 14). Although these reduction levels may not be regarded as sufficient to fulfill the targets of emission reductions, such strategies provide the basis for additional measures to reduce acidic emissions in cost efficient ways.

8 Conclusions

Both Integrated Assessment Models (such as the RAINS model) and energy-emission models (such as the energy flow optimization model EFOM-ENV) can be used to estimate emission control costs on a national and international level. Whereas the analysis in Integrated Assessment Models is usually limited to "add-on" technologies for emission reductions on a relatively high level of aggregation, energy-emission models also include the potential for structural changes of

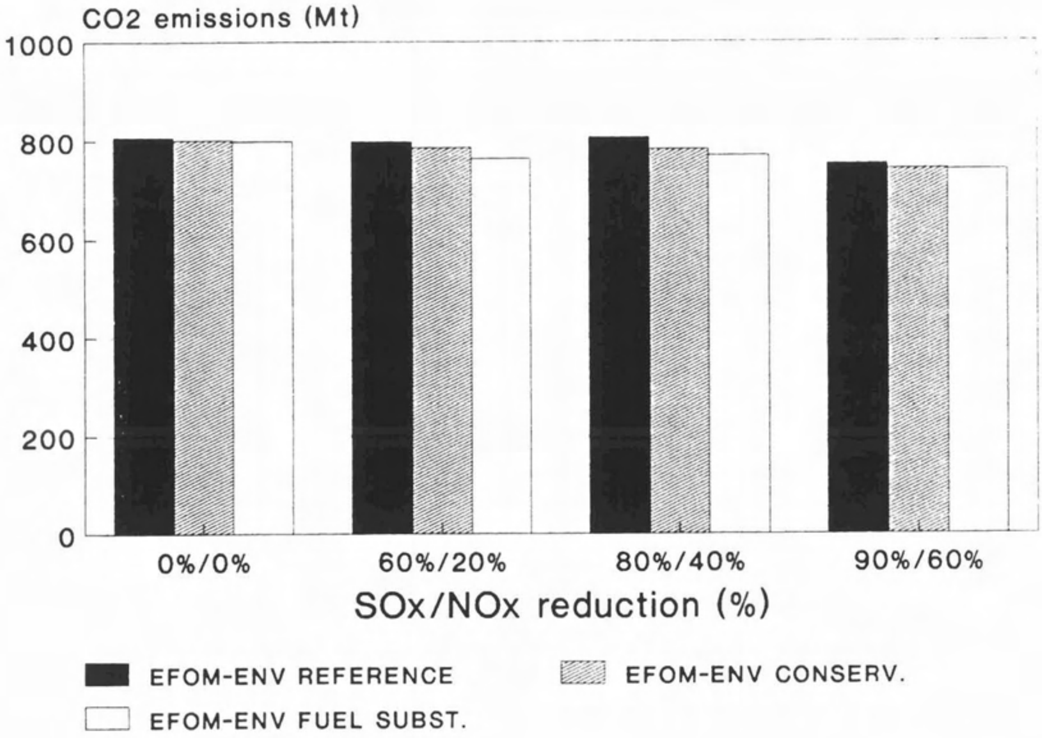

Figure 13: CO_2 emissions of SO_2/NO_x reduction strategies

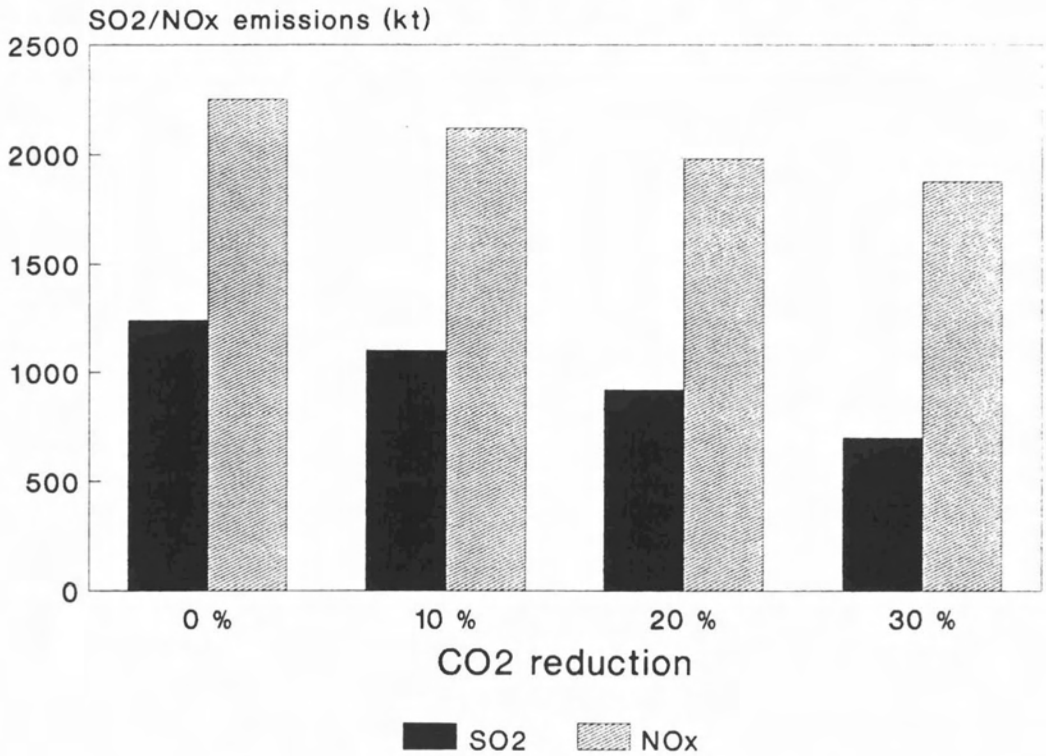

Figure 14: SO_2 and NO_x emissions of CO_2 reduction strategies

the energy system (e.g. energy conservation, fuel and technology substitution) usually with a large amount of technical and economic details.

It has been demonstrated that – within certain and well defined limitations – the simplified analysis of emission control costs, as it is implemented in Integrated Assessment Models (such as the RAINS model), provides results which are consistent with the more complex model approach of optimizing energy-emission models (e.g. EFOM-ENV). Differences can be identified and traced back to different assumptions and input data.

By taking these structural changes into consideration the systems approach of energy-emission models can be used to identify cost efficient strategies to achieve prespecified emission reduction levels. It has been demonstrated that both energy conservation and fuel substitution enable a certain cost saving potential for emission reductions, but that this depends largely on whether the possibility for such changes is provided by the systems. Specifically, this means that cost savings are smaller in cases when an inflexible infrastructure meets stable or declining energy demand and when only short time periods are analyzed. On the other hand, increasing energy demand and long time horizons for the analysis can provide the potential for considerable cost savings.

If such structural changes are intentionally utilized for emission reductions the simplified model approach of Integrated Assessment Models results in a systematic overestimate of emission control costs. As soon as structural changes of the energy system are utilized as elements of emission reduction strategies, the 'systems approach' of energy-emission models is indispensible for cost-efficient solutions.

It has been demonstrated that the completeness of the analysis for all emission sources is of vital importance for the overall accuracy of the results. The exclusion of a single sector may result in a severe overestimate of abatement cost.

Simultaneous consideration of emission reductions for several pollutants also provide the potential for cost savings. As demonstrated in the example of West Germany, a CO_2 constrained energy strategy may serve as an efficient basis for further SO_2 and NO_x reductions.

Although both the RAINS and the EFOM-ENV models are now fully operational, some further improvements could increase the usefulness of their results considerably:

- Both models should be under permanent review in order to guarantee the full representation of relevant emission control options. This applies in particular to those sectors, where only limited experience is currently available internationally and which are consequently often excluded from consideration.

- If fuel substitution strategies are adopted on a wide international scale as important elements of emission reduction policies, the potential price reactions of primary energy due to dramatically changing fuel demands have to be taken into account.

- Since estimates of emission reduction costs usually rely on a number of assumptions, emphasis should be concentrated on identifying those elements of reduction strategies, whose selection do not depend only on a few assumptions. Models should provide tools for developing robust conclusions.

References

[1] Alcamo J., R. Shaw, and L. Hordijk (1990) (ed.): *The RAINS Model of Acidification. Science and Strategies in Europe.* Dordrecht, Netherlands: Kluwer Academic Publishers.

[2] Amann M. (1990): *Energy Use, Emissions and Abatement Costs in Europe.* In *the RAINS Model of Acidification. Science and Strategies in Europe,* edited by J. Alcamo, R. Shaw and L. Hordijk. Dordrecht, Netherlands: Kluwer Academic Publishers.

[3] BEIJER Institute (1987): *Acid Deposition in Europe: Coordinated Abatement Strategies,* Interim Report. Stockholm, Sweden: BEIJER Institute.

[4] Commission of the European Communities (1990) (ed.): *Energy and Environment: Methodology for Acid Air Pollution Assessment for Europe.* Brussels, Belgium.

[5] Office for Official Publications of the European Communities (1985) (ed.): *EUROSTAT, Thema 4, Series A, Energy-statistical Yearbook.* Luxembourg.

[6] Fishbone L.G., and H. Abilock (1981): *MARKAL - a linear programming model for energy systems analysis. Technical description of the BNL version.* International Journal of Energy Research, Vol. 5:353.

[7] Guilmot J.-F., D. McGlue, P. Valette, and C. Waeterloos (1986): *Energy 2000.* Cambridge, UK: Commission of the European Communities, Cambridge University Press.

[8] International Energy Agency (1989): *Coal Information 1989.* Paris, France.

[9] Messner S. (1984): *User's Guide for the Matrix Generator of MESSAGE-II.* Working Paper WP-84-71. Laxenburg, Austria: International Institute for Applied Systems Analysis.

[10] Plinke E., H.-D. Haasis, O. Rentz, and M. Sivrioglu (1990): *Analysis of Energy and Environmental Problems in Turkey by Using a Decision Support Model.* AMBIO Vol. 19(2):75-81.

[11] Rentz O., H.-D. Haasis, T. Morgenstern, J. Remmers, and G. Schons (1990): *Optimal Control Strategies for Reducing Emissions from Energy Conversion and Energy Use in all Countries of the European Community.* Karlsruhe, Germany: KfK-PEF series, Vol. 72.

[12] Russ P., E. Plinke, T. Morgenstern, F. Perello-Aracena, H.-D. Haasis, and O. Rentz (1990): *Energy and Environment: Strategies for Acid Pollutant Reduction in the European Community.* International Journal of Energy Research, 833-847.

[13] Streets D.G. (1990): *Integrated Assessment: Missing Link in the Acid Rain Debate?* Environmental Management Vol. 13(4):393-399.

[14] UN-ECE (1990): *Using Critical Loads as Basis for Abatement Strategies in Europe.* UN-ECE Report EB.AIR/WG.5/R.7. Geneva, Switzerland.

[15] Van der Voort E., *et al.* (1984): *Energy Supply Modeling Package EFOM 12C. Mark I, Mathematical Description.* Louvain-la-Neuve, France.

[16] Walbeck, M., H.-J. Wagner, D. Martinsen, and V. Bundschuh (1988): *Energie und Umwelt als Optimierungsaufgabe.* Berlin, Germany.