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Abstract

Emissions of CO_2, SO_2 and NO_x are all closely linked to burning of fossil fuels. Here we report on simulations done by linking a Sectoral European Energy Model (SEEM) covering energy demand in nine Western European countries with the emission-transportation-deposition model RAINS developed by IIASA. The study analyses emissions of CO_2, SO_2 and NO_x, and deposition of sulphur and nitrogen in year 2000 under four different energy scenarios. Two different sets of future behavioural patterns for the thermal electric power production sector is considered. In one regime, called the plan efficient regime, the sector is assumed to follow official plans with regard to investment in new capacity. In the other regime, called the cost efficient regime, the power sector is assumed to behave in a cost minimising manner. The effects of the proposed EC carbon/energy tax are studied under both regimes, giving rise to altogether four scenarios. In both regimes the effect of the EC tax is to reduce emissions by between 6 and 10 per cent in year 2000 relative to the scenarios without the tax. A change of regime, from the regulated plan efficient regime to the market based cost efficient regime, will by itself reduce emissions of CO_2 and NO_x by approximately 3 per cent, while SO_2 emissions are reduced by 13 per cent.

Although the emission reductions may seem modest, they are shown to have a sizeable effect on the technological abatement costs of reaching targets like those prescribed in the Sophia protocol on the stabilisation of NO_x emissions, and the Helsinki protocol on SO_2 emission reductions.

Keywords: Mathematical and quantitative methods - Forecasting and other model applications (C53); Agricultural and natural resource economics - Environmental management (Q2); Energy - demand and supply (Q41)

1. Introduction

Negotiations are in progress on protocols to control sulphur dioxide (SO_2) and nitrogen oxide (NO_x) emissions in Europe. Many difficulties concerning the underlying principles, emission levels and burden sharing lay ahead of these negotiations. At the same time the Commission of the European Communities (EC) has proposed "a community strategy to limit carbon dioxide (CO_2) emissions and to improve energy efficiency" in the form of a combined carbon/energy tax. This tax, if implemented, will obviously also influence the emissions and depositions of SO_2 and NO_x. This paper analyses the effects of the carbon/energy tax as proposed by the EC on future CO_2, SO_2 and NO_x emissions. We use a Sectoral European Energy Model (SEEM) with inter fuel substitution developed by Statistics Norway to forecast fossil fuel use. SEEM is a model of the demand side of the energy markets in 9 European countries, together covering approximately 80 per cent of the energy consumption in OECD Europe in 1989. Also included in SEEM is a module converting demand for fossil fuels (solid, liquid and gaseous) into estimates of CO_2 emissions. To assess the effect of a carbon/energy tax on SO_2 and NO_x emissions, energy paths as projected by SEEM are linked to the Regional Acidification Information and Simulation (RAINS) model, developed at the International Institute for Applied Systems Analysis, IIASA.

The simulations of energy demand in the SEEM countries turn out to be very sensitive to the modelling of the electric thermal power generating sector. For this reason we consider two *regimes*. In the *plan efficient regime* the thermal power generating sector is supposed to invest in new capacity according to national plans as reported to IEA (1991). Thus thermal power production is strictly regulated in this regime. In contrast to this, the *cost efficient regime* describes a situation where the thermal power producing sector is assumed to behave in a cost minimising way. Altogether we will therefore consider four scenarios;

i) A reference scenario under the plan efficient regime without the EC tax (scenario 1).

ii) A scenario with the EC tax, but still in the plan efficient regime (scenario 1t).

iii) A scenario without the EC tax in the cost efficient regime (scenario 2).

iv) A scenario in the cost efficient regime with the EC tax (scenario 2t).

The base year for the calculations is 1990[1], and the horizon is the year 2000. Output from SEEM replaces energy variables in RAINS for all fuel types, sectors and countries covered by SEEM. RAINS variables relating to countries or sectors not covered by SEEM are taken from RAINS (Version 6.0) "root scenario"; the Official Energy Pathway (OEP). The SO_2 and NO_x emissions calculated by RAINS are in accordance with the technology specification in this RAINS scenario.

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[1]Strictly speaking SEEM is calibrated to the year 1988. Year 1990 is therefore simulated.

RAINS also makes it possible to calculate national *deposition* levels of sulphur and nitrogen and to estimate the extent of national areas where the critical load of sulpur is exceeded under the various scenarios. Finally, employing the national sulphur and nitrogen abatement cost curves implemented in RAINS, it is possible to indicate changes in abatement costs associated with an introduction of the carbon/energy tax or a change of regime in thermal power production.

2. A brief outline of SEEM and the link to RAINS

The presentation of SEEM is restricted to a rather brief outline of the energy model and a somewhat more detailed description of the "soft link" to RAINS. A more detailed documentation of SEEM is given in Birkelund et al. (1993a). RAINS is also well documented elsewhere (Alcamo et al., 1990).

SEEM covers the following nine West-European countries: the four major energy consumers Germany (west), France, Italy and UK, the Netherlands as a major gas country, and the four major Nordic countries Sweden, Denmark, Finland and Norway. These countries together consumed about 80 per cent of the OECD Europe total energy use in 1989.

Each country is treated as a separate block in a *demand* model, i.e. we are not concerned with the *supply* of primary energy. Supply of thermal electric power is however modelled. In each country there are six sectors: Power production, Manufacturing industries and Service industries (in the following denoted Industry and Services), Households, Transportation and Other activities.

In SEEM the *industry* sector is described by a two level Cobb Douglas fuel share model. The lower level determines a cost minimising combination of energy commodities, while at the upper level a cost minimising combination of capital, labour and energy is ascertained. Hicks neutral technical progress is specified at the upper level. The lower level is calibrated using fuel consumption cost shares. On the upper level we calibrate using elasticities found in other studies, see Birkelund (1990). To allow for lags in the adjustment of capital to price changes, demand is lagged according to a partial adjustment hypothesis.

For the *service sector* we postulate a Constant Elasticity of Substitution (CES) fuel share model with weak separability between two or three levels, depending on the numbers of energy carriers used. At the bottom level oil and natural gas is aggregated to an oil-gas commodity. At the intermediate level, this aggregate is combined with solid fuel into a fossil fuel aggregate. Finally, at the upper level fossil fuel and electricity are separate inputs in a log-linear model of energy demand, i.e., the full energy aggregate is neither separable nor homothetic. This implies a hypothesis that the use of electricity contributes to production in a different manner from fossil fuel. While the latter is mainly used for space heating, electricity is mostly used for appliances like computers and lightning for which energy substitution is limited. The parameters at the upper level are calibrated, while the lower and intermediate parameters are estimated.

Household energy demand is modelled by a Discrete Continuous Choice (DCC) model. The discrete part of the model corresponds to the choice of fuel for space heating, while the continuous part determines the level of energy demand, given the choice of heating system. Transitions among fuels make the model dynamic, and a parameter reflecting the degree of "habit persistence" held by consumers is included. The model has been estimated on a cross section of data from seven European countries, see Bartlett et al. (1987). However, some parameters of the model are calibrated in order to bring the direct fuel price elasticities more in line with those estimated in a study made by Chern et al. (1983). The household model for Norway is based on a Linear Expenditure System and is described and estimated in Haug (1992).

The *transport sector* is divided into four main groups; road transportation, rail, domestic shipping and aviation. Road transport is further divided into passenger transport and non-passenger transport. Vehicles can be run on gasoline or auto diesel. Log-linear demand functions for each of the four road transportation segments are defined in the model. For each segment the amount of road transportation services demanded is produced by suppliers in a two step cost minimising procedure. First, the optimal number of vehicles (capital) and utilisation of each vehicle is determined given the demand for transportation services. In the second step a cost minimising combination of fuel and other variable inputs per vehicle is found. Autonomous technical change is allowed for in the relation of fuel use per vehicle. The cost share parameters on the lower level are based on three surveys, Dahl (1986), NOS (1980) and Eidhammer (1984), and are set equal for all countries. The parameters at the upper level are given country specific values such that total fuel price and income elasticities are equal to those estimated by Dargay (1990). The demands for fuel in aviation and electricity in rail transportation are estimated as log-linear functions with GDP and fuel prices as arguments. Other fuels for rail transportation and fuels for domestic shipping are exogenous to the model.

The *electricity generation* model focuses on the supply of thermal power. By adding end user demand for electricity to the exogenously forecasted net export and the calculated losses in transfer and distribution, total domestic power production requirements are derived. Deducting the exogenously forecasted supply of hydro, nuclear and other power yields residual demand for thermal power, supplied either by existing plants or new capacity. New capacity is defined by the gap between demand for thermal power and the remaining capacity from the previous period. We assume no substitution possibilities in incumbent capacity, thus disregarding dual fuel systems. New capacity fossil fuel input shares are functions of relative marginal fuel costs. The fuel shares are specified as Cobb Douglas functions. In the *plan efficient regime* (see below) parameter values are adjusted such that official plans for the domestic power sector are fulfilled. In the *cost efficient regime* cost minimising behaviour is assumed. The Norwegian power system is almost exclusively based on hydro power. Consequently hydro power is endogenous and thermal power production is subject to exogenous projections. Hydro power production is based on the long term marginal cost of expanding the system. Electricity prices are calculated as a function of long term marginal costs, taxes and residual markups. For the other countries changes in electricity prices are based on changes in thermal power production costs. Constant return to scale is assumed, implying that electricity prices are determined by average costs based on fuel and capital inputs, thermal power production costs, adding sector specific markups and taxes.

Figure 1. The structure of SEEM and the links to RAINS

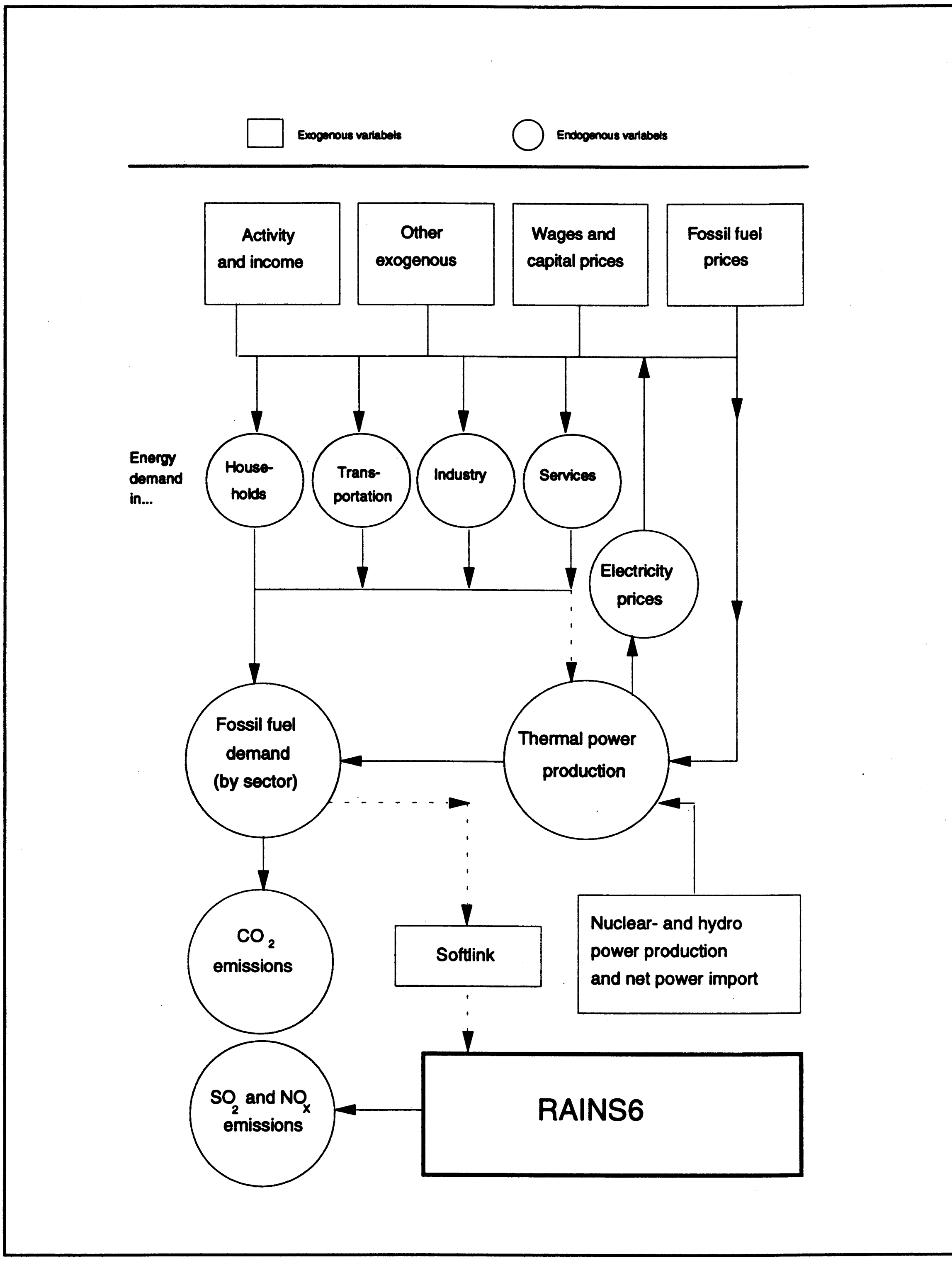

Figure 1 depicts the structure of each country model in SEEM. As a first step the model determines the demand for solid fuels, oil, natural gas and electricity in the end user sectors. The electricity producing sector then derives the need for domestic production of thermal power, given a set of (exogenous) plans for power production by renewable and nuclear sources. On the basis of costs in thermal power production the model calculates electricity prices in all sectors. The model is thus simultaneous in the electricity market, where the equilibrium set of prices is defined when supply equals demand for electricity. Adding the use of fossil fuels in the end user sectors to fossil fuel inputs in thermal power production, total demand for each fossil fuel is derived by country. In a sub model emission coefficients for CO_2 are linked to the consumption of solids, oil and natural gas. Only anthropogenic emissions of CO_2 from fossil fuels are covered[2]. Likewise the end use of fossil fuels is linked to RAINS in order to calculate SO_2 and NO_X emissions. The link, market by a dotted line in figure 1, is further described below.

In both the plan efficient and the cost efficient regime the demand for thermal power is derived from electricity demand in the end user sectors (endogenous) and IEA-based plans for supply of hydro, nuclear and other power (exogenous). The residual thermal power demand is covered by either existing plants or new capacity.

Figure 2 indicates the structure of energy input and output in RAINS and SEEM respectively and the soft link between the two. SEEM forecasts fossil energy consumption by the fuel aggregates solid fuels, oil, and natural gas. The energy input in RAINS is less aggregated than the output in SEEM. In addition it is no one-to-one correspondence between the sector split in SEEM and RAINS. A procedure to allocate the energy aggregates in SEEM to the corresponding coal and oil products in RAINS, and a fit to the RAINS sectors was thus needed. We disaggregated the energy consumption in the economic sectors of SEEM into RAINS fuel types by applying the ratio between fuel types as given by RAINS for the year 1990. The domestic sector in RAINS corresponds to the sum of services, households and other activities in SEEM. The shaded area in the figure shows the sectors where SEEM does not provide output to RAINS or fuels that are of no importance in this context. These entries are thus kept at the same levels as in the OEP for the years 1990 through 2000[3].

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[2] The emission factors in terms of million metric tons of CO_2 per million ton oil equivalents (mtoe) are 2,4 for natural gas, 3,1 for oil, 3,9 for hard coal and 4,6 for brown coal in all sectors.

[3]Comparing the SEEM based scenario 1 with OEP from RAINS, we find that the initial energy input is approximately 2 per cent higher in SEEM than in RAINS, and that this divergence increase to almost 9 per cent in year 2000, mainly due to a faster growth in the transport sector. Thus, NO_X emissions are 15 per cent higher in SEEM than in OEP/RAINS in year 2000, while the SO_2 emissions are 7 per cent higher.

Figure 2. Linking SEEM output to RAINS input. Shaded areas are unchanged

Output from SEEM (Mtoe)

	Power	Services	Househ.	Other	Transport	Industry
Solids	10.4	6.0	0.0	0.0	0.0	10.1
Oil	2.3	1.5	14.2	2.8	42.3	6.7
Natural gas	0.7	6.4	6.4	0.1	0.0	8.7

DOM

Input from RAINS (OEP) to softlink (PJ)

	CON	PP	DOM	TRA	IND	OTH
BC	0	0	0	0	0	0
HC	64	381	26	0	115	0
DC	0	0	33	0	231	0
MD	0	0	762	583	89	0
HF	210	73	70	0	163	0
LF	115	0	0	1084	133	409
GAS	21	15	548	0	472	0
OS	0	9	132	0	26	0
NUC	0	2963	0	0	0	0
HYD	0	495	0	0	0	0
ELE	252	-1503	633	35	416	0
DH	0	0	0	0	0	0

6,7Mtoe 42,3PJ/Mtoe $\frac{89}{89+163+133}$

Input to RAINS (PJ)

	CON	PP	DOM	TRA	IND	OTH
BC	0	0	0	0	0	0
HC	64	431	35	0	132	0
DC	0	0	44	0	266	0
MD	0	0	719	626	65	0
HF	210	96	66	0	120	0
LF	115	0	0	1164	98	409
GAS	21	31	542	0	370	0
OS	0	10	176	0	30	0
NUC	0	2963	0	0	0	0
HYD	0	495	0	0	0	0
ELE	252	-1503	633	35	416	0
DH	0	0	0	0	0	0

3. Basic assumptions and initial situation

A summary of the most important exogenous assumptions underlying all the scenarios is presented in table I, while table II presents baseline annual economic growth rates over the period 1990-2000. In addition table II gives base year emissions as shares of total emissions in the SEEM model area, national shares of thermal power in the production of electricity and the shares of fossil fuels in energy consumption in the SEEM countries in 1990.

Table I. Exogenous variables

	Average annual growth (percent) 1990-1995	1995-2000	Comments
Power production:			
Hydro power	3,35	1,17	Hydro power includes both hydro and other power. The surge in hydro power before 1995 is due to growth in other power. Source: IEA and CBS
Nuclear power	1,98	0,58	Source: IEA and CBS
Technical progress in:			Autonomous in all sectors. Source: Statistics Norway and ITE*
Households and Industry	0,70 - 0,75	0,70 - 0,75	
Services and Transport	1,10 - 1,20	1,10 - 1,20	
Real GDP growth	-0,15 - 2,1	2,0 - 2,9	Growth rates in services and manufacturing are somewhat higher, respectively lower, than the GDP rate while private consumption keeps up with the GDP growth. Source: Statistics Norway and DRI (1990a)**
Capital costs	Constant in real terms		Source: Statistics Norway
Labour costs	Follows the real GDP growth rate		
Import energy prices, CIF:			Source:ETSAP (1991)***
Coal	0,18	0,18	
Oil	2,14	2,14	
Natural gas	2,14	2,14	

* ITE=Institute of Transport Economics, Oslo, Norway
** DRI=Data Resources Institute, USA
*** ETSAP=Energy Technology System Analysis Program

Table II. Average annual GDP growth 1990-2000, emission shares, shares of thermal power in electricity production and fossil fuels in energy consumption in 1990. Per cent

	Real GDP growth rates 1990-2000	CO_2 shares	SO_2 shares	NO_x shares	Thermal power shares	Fossil fuel shares
Denmark	2,1	2	2	2	97	99
Finland	1,2	2	4	2	31	69
France	2,5	15	13	19	13	59
Germany (west)	2,5	30	19	27	62	85
Italy	1,9	16	25	16	83	94
The Netherlands	2,2	7	3	6	94	98
Norway	2,1	1	1	2	1	22
Sweden	0,9	2	2	3	3	41
United Kingdom	2,1	24	32	24	78	92

The proposed EC tax is a tax based partly on an energy component and partly on a carbon component, where the energy component of the tax should not exceed 50 per cent. A $3 per barrel tax is assumed to be introduced in 1993 with an additional $1 per barrel in successive years until 2000. Note that the carbon/energy tax is superimposed on the existing excise tax systems. Also, in the simulations the economic activity levels are assumed fixed. I.e. we disregard any effects of the tax on economic growth and its composition and only consider substitution effects among the energy carriers[4].

To ensure that the model holds the desired properties in the *plan efficient regime*, the fuel shares in thermal power production are specified as Cobb Douglas functions with fuel prices as arguments. Parameter values are adjusted so that:

[4]A key characteristic of the EC tax proposal is revenue neutrality. A number of studies have considered the impact of carbon taxes on GDP, see DRI (1990b), NOU (1992), Agostini et al. (1992), Manne and Richel (1991) and Berniaux et al. (1991). The estimates for Europe seem to be in the range of 1-3 per cent loss in GDP, depending on the tax rate and the speed of implementation among other things. This may justify the constancy of economic growth across scenarios.

a) The fuel shares for the given price set yields the base year investment shares for the respective fuels.

b) Given the relative price path, the fuel shares of the national investment plans are as reported in IEA (1991).[5]

The plan efficiency assumption reflects the regulated nature of the power production sector in the European countries. National governments, in coherence with dominating and protected utilities, make plans for investment and production. The reference path thus reflects the priorities of national energy policies as of 1991. The costs of these policies are covered by electricity consumers by a mark-up mechanism. This reflects the most common pricing policy by electric utilities.

It may seem inconsistent to let the producers of thermal power react as economic agents to carbon taxes while they else are to fulfil government plans for production. However, carbon taxes certainly increase thermal power production costs. Under a regulated regime such costs will be passed on to the consumers through higher electricity prices. Thus, less electricity will be consumed and less fossil fuel input will be used in the power production. This scale effect is reflected in our model. Also, since cost considerations are part of a planning process, the cost of taxes will be reflected in the fuel shares.

In the *cost efficient regime* we focus on the substitution of natural gas for coal, while the assumption of a constant oil share is maintained. The fuel shares for coal and gas are functions of long term marginal production costs in the Best Available Technologies, BAT. Coal and gas compete for the remaining fuel share after subtraction of the marginal oil share, which is set equal to the one in the plan efficient regime. From published data in a number of papers on the generation technology (see e.g. IEA, 1992 and Elkraft/Elsam, 1990), reliable estimates on capital and operating costs for gas combined cycle and coal fired plants can be derived.

For a given price path of coal, the break-even price of gas in BAT is a function of the capital and operating costs. Capital costs are in turn functions of lifetimes, investment costs, load factors and discount rates. The data on these variables in BAT varies. To avoid a bias in favour of gas, we have chosen high estimates of capital costs for gas compared to those of coal (compared to the average estimate).

The fuel shares for coal and gas are specified by a logit function. The logit function is calibrated to distribute the marginal fuel shares equally between coal and gas when the cost of marginal coal power

[5]In general, the electricity demand forecasts made by the individual governments are not equal to the reference scenario. Because of this the thermal power fuel use in the reference path diverges from the official plans reported in *Energy Policies And Programs of IEA Countries (1991)*.

equals that of gas. It is further designed to distribute less than 10% to a fuel when its marginal production cost is 10% higher than that of the other. We admit that the calibration of the logit function is a matter of subjective judgement. Even if there were agreement on the break even estimate, it would depend on country specific parameters, as capital costs depend on national cost levels. Besides, there is no such thing as a given expectation of the price of coal. These matters justify the use of a logit function, with some probability of choosing coal even if the gas price expectation is above break even, and vice versa. They do not, however, necessarily justify the uniform choice of the (10%, 10%) intersection. The model can easily be recalibrated to alternative choices.

Compared to the simulations under the plan efficient regime there are no changes to any other exogenous variables. The only difference between the two regimes is thus the investment behaviour in the thermal power sector.

4. Results in the plan efficient regime

Table III lists the results for CO_2, SO_2 and NO_x emissions and fossil fuels use in the plan efficient regime without and with the EC carbon/energy tax (scenario 1 and 1t, respectively). The projected emission levels in year 2000 in the tax scenario is compared to "targets" defined as follows: For CO_2 the target is stabilisation at the 1990 level, for SO_2 the target is a 30 per cent reduction relative to the 1980 level, while the NO_x target is a stabilisation at the 1987 level. The SO_2 and NO_x targets correspond to national targets as expressed in the Helsinki and Sophia protocol, respectively, although they refer to different end years.

Table III. Emissions and energy use under the plan efficient regime without and with a carbon/energy tax (scenario 1 and 1t)

	Scenario 1				**Scenario 1t**	
	Level		Annual growth (%)		Tax impact. Difference between scenario 1 and 1t (%)	Deviation from targets (%)
	1990	2000	1990-1995	1995-2000	2000	2000
CO_2 (Mill.tons)	2 346	2 576	0,0	1,9	-9,4	-0,5
SO_2 (Kilo tons)	13 479	12 739	-1,5	0,4	-7,4	-2,5
NO_x (Kilo tons)	11 864	13 037	-0,1	2,0	-6,2	13,4
Solids (Mtoe)	222	239	0,8	2,3	-14,9	
Oil (Mtoe)	359	366	0,5	0,9	-5,1	
Natural gas (Mtoe)	173	233	2,8	3,2	-8,0	

To get a grasp of the main mechanisms behind the emission projections presented in table III, we start with a brief overview over the energy use in the plan efficient regime (scenario 1).

The increased demand for natural gas, mainly driven by official plans for the thermal power sector, results in an annual growth rate of nearly 3 per cent throughout the simulation period. Solids consumption, mainly coal used in the power sector, suffers from low investment in coal fired power plants. Along with weak economic growth before 1995, coal and oil consumption increase only moderately. As economic growth is expected to recover towards 2000, the coal and oil consumption increase at annual growth rates of 2,3 and 0,9 per cent, respectively. The growth in oil consumption is thus still well below the average rate of economic growth in this period.

The CO_2 emissions accelerate towards the turn of the century with an average annual growth rate of almost 2 per cent between year 1995 and 2000. By the end of the simulation period the CO_2 emission level is thus 10 per cent higher than the simulated 1990 level, i.e. 10 per cent above the stabilisation target. The power and transport sectors are the main contributors to the CO_2 emissions, with shares equal to 32 and 27 per cent, respectively in 1990. Their shares increase somewhat throughout the simulation period. The growths in CO_2 emissions from the households and the service sector are more moderate, while emission from industry drops 9 per cent over the period.

The introduction of the EC tax in 1993 is just sufficient to meet the CO_2 stabilisation target by the year 2000, but if a long term stabilisation of carbon dioxide emissions is sought by tax measures, the tax will have to rise also beyond year 2000. This simply reflects that the shadow price of the emission constraint increases over time as energy demand increases.

The simulation indicates that the growth in the total NO_x emissions in scenario *1* follow that of the CO_2 emissions. The NO_x emissions in the transport sector almost keep up with the growing end use of energy in that sector of 17 per cent from 1990 to 2000. The emission patterns in the industry and domestic sector also show the same pattern as experienced for CO_2 emissions. RAINS divides the coal input into new and old power plants in a way that mitigates the implicit emission factors for coal in the power sector.[6] This RAINS feature virtually neutralises the growth in NO_x emissions coming from natural gas use in the power sector. In addition the energy use in the conversion sector (exogenous) shows a 5 per cent drop from 1990 to 2000.

There are no interfuel substitution possibilities in the transport sector and sectoral energy taxes are generally high. Both of these facts are important for the NO_x emissions, since emissions from the transport sector amount to almost 70 per cent of the total NO_x emissions in the model area in year 2000. Although the effect of the carbon/energy tax in scenario *1t* is to reduce NO_x emissions by only 4 per cent in the transport sector, it accounts for nearly 3 of the total 6 per cent reduction in the total NO_x emissions. The industry and power sectors are relatively more influenced by the EC tax, but as their relative weights are only 5 and 16 per cent of the total NO_x emissions, they only account for 1 and 2 per cent of the reduction, respectively. NO_x emissions in the domestic sector account for only 5 per cent of total emissions. Due to a high initial price level, the EC tax has only a modest effect on the relative prices in this sector. Emissions from the domestic sector thus experience the least relative reductions and are almost negligible in a tax induced NO_x abatement context. The EC tax is insufficient to reduce the NO_x emissions to 1987 level by the year 1994 as required by the Sophia protocol.

Although use of fossil fuels increases from 1990 to 2000 in the plan efficient regime, the SO_2 emissions decrease by almost 6 per cent over the same period. This is due to several factors. Recalling the soft link, we divided the oil aggregate from SEEM into several oil products to fit into the RAINS-input matrix. In our simulation we experience a reduction in oil consumption in countries with relatively high consumption of heavy oil and a corresponding increase in countries that uses lighter oil products. As a

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[6]RAINS divide the input of hard coal in the power sector into hard coal used in wet- and dry bottom boilers such that one experience a change to the latter towards year 2000. Thus, the implicit emissions factor for hard coal used in the power sector decrease. In our plan efficient regime this effect dominates the increase in emissions from higher use of hard- and brown coal in the sector.

result the total input of **heavy** oil in RAINS decreases by nearly 18 per cent from 1990 to 2000, despite a total increase in the aggregated oil input from SEEM of 2 per cent in the same period. The SO_2 emission factors for light fuel oil, natural gas and other fuels are zero in RAINS.

The power sector followed by domestic sector are the main contributors to SO_2 emissions with a relative importance of about 56 and 11 per cent respectively in year 2000 in scenario 1. The transport sector only makes up for some 5 per cent of the SO_2 emissions. The largest relative effect of the tax is found in the industry sector with a 23 per cent drop in SO_2 emissions, largely due to lower hard coal and heavy oil use. This accounts for over 2 of the total 7 per cent reduction in the SO_2 emissions. The power sector accounts for over 4 per cent of the tax induced SO_2 reductions. For the same reasons as for NO_x the domestic sector is unimportant for the total tax induced SO_2 abatement. The tax induced SO_2 abatement is sufficient to meet the target emission levels corresponding to the 1985 Helsinki protocol.

5. Changing investment mechanism: The cost efficient regime

Table IV reports the CO_2, SO_2 and NO_x emissions and fossil fuels use in the cost efficient regime without and with the EC tax (scenarios 2 and 2t). In addition it lists the effect of deregulating the thermal power sector measured as the percentage shift between the plan and cost efficient regime before the EC tax is implemented.

The table suggests that the effects of introducing cost based investment decisions by thermal power producers on total energy use and emissions are substantial. Obviously, the shift of regime has the largest impact on the electricity sector, but another impact is the lower **average** production cost in the thermal power sector. The savings are passed on to electricity consumers, causing substitution of electricity for fossil fuels in the end use sectors. The difference between the demand for thermal power in the two reference scenarios can thus be interpreted as a scale effect resulting from the shift of regime. However, by year 2000 the effect accumulates to only 2 per cent. The explanation for this small effect is that cost efficient investments in new thermal power capacity only pays off as the discrepancy in capital stock in the power sector increases between the two regimes.

Table IV. Emissions and energy use in the SEEM area under the cost efficient regime without and with the carbon/energy tax (scenario 2 and 2t)

	Scenario 2			Scenario 2t		
	Level	Annual growth. %		Difference between scenario 1and 2 (%)	Tax impact. Difference between scenariò 2 and 2t (%)	Deviation from targets. (%)
	2000	1990-1995	1995-2000	2000	2000	2000
CO_2 (Mill.tons)	2 486	-0,2	1,4	-3,5	-9,7	-4,3
SO_2 (Kilo tons)	11 080	-2,2	-1,6	-13,0	-9,3	-16,9
NO_x (Kilo tons)	12 725	-0,3	1,7	-2,4	-6,4	10,4
Solids (Mtoe)	184	-2,6	-1,1	-22,9	-20,5	
Oil (Mtoe)	366	-0,4	0,8	0,2	-5,1	
Natural gas (Mtoe)	285	4,7	5,5	22,2	-5,1	

While oil consumption is nearly unaffected by the deregulation at the end of the simulation period, the consumption of natural gas increase by 22 per cent at the expense of coal. As the emission factors of coal are higher than those of natural gas, deregulation of the power sector reduces the emissions.

Least effected are the NO_x emissions, which mainly come from the almost unaffected transport sector. As the power sector plays an important role for CO_2 emissions, the 3,5 per cent reduction may also seem disappointingly low. However, the difference between the CO_2 emission factors of natural gas and coal is too low to cause major shifts in total CO_2 emissions. The SO_2 emissions within the SEEM model area, which largely stem from power production, decline by 13 per cent compared to the plan efficient regime at the end of the simulation period. This relatively large effect is partly explained by the fact that the shift in regime takes place in a sector that dominates the emissions in question and because natural gas does not emit SO_2 when burned. A cost efficient thermal power sector is thus more effective in a SO_2 abatement context than the EC carbon/energy tax applied under a plan efficient regime.

Comparing the performance of the EC tax under the cost efficient regime with the same tax policy under the plan efficient regime, we find that the impact of the EC tax on oil consumption are almost identical. Power production dominates the use of solids and natural gas. Improved cost incentives in this sector thus increase the tax effect on solids consumption to 21 per cent compared to the 15 per cent effect in the plan efficient regime. For natural gas consumption the impact is reduced to 5 compared to 8 per cent in the former regime. Simulations beyond 2000 show, however, that natural gas consumption will benefit from the planned EC tax in a cost efficient regime in the longer run, see Birkelund et al. (1993b).

The simulation indicates that the deregulation of the thermal power sector not only reduces the emission levels, but also enhances the performance of the EC carbon/energy tax. The enhanced abatement effect in the deregulated tax scenario, measured as impact on the non tax scenario, is moderate though for NO_X and CO_2. EC tax induced SO_2 abatement on the other hand, increases nearly 2 per cent compared to the plan efficient regime in year 2000.

Figures 3a-c summarise the simulated CO_2, SO_2 and NO_X emissions under both regimes, with and without the EC tax.

Figure 3a. Simulated CO_2 emissions under both regimes, with and without the EC tax

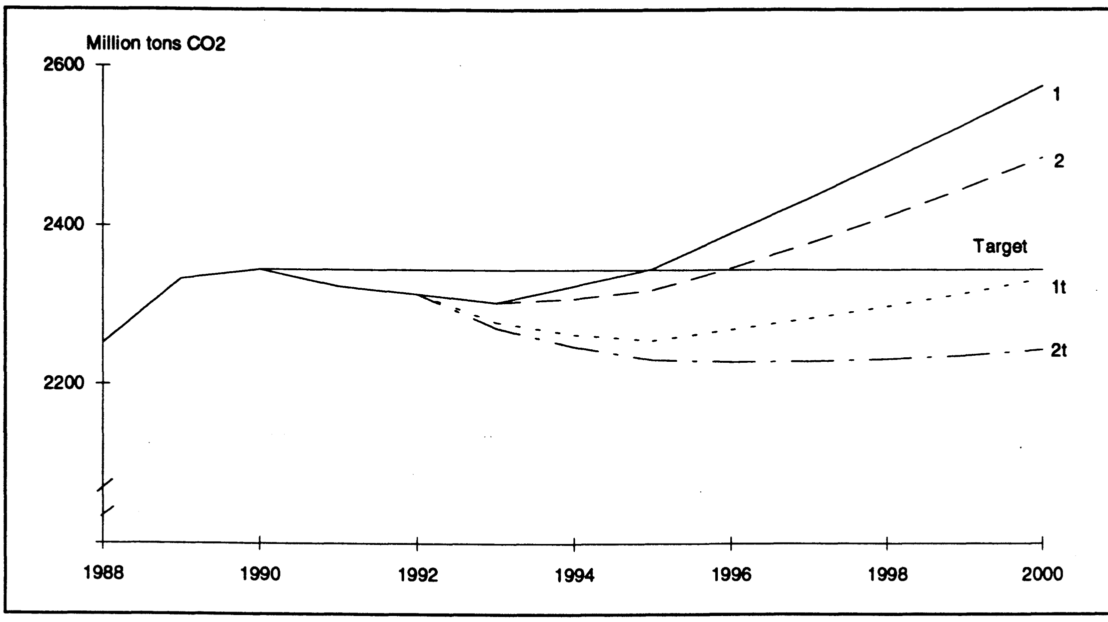


Figure 3b. Simulated NO_X emissions under both regimes, with and without the EC tax

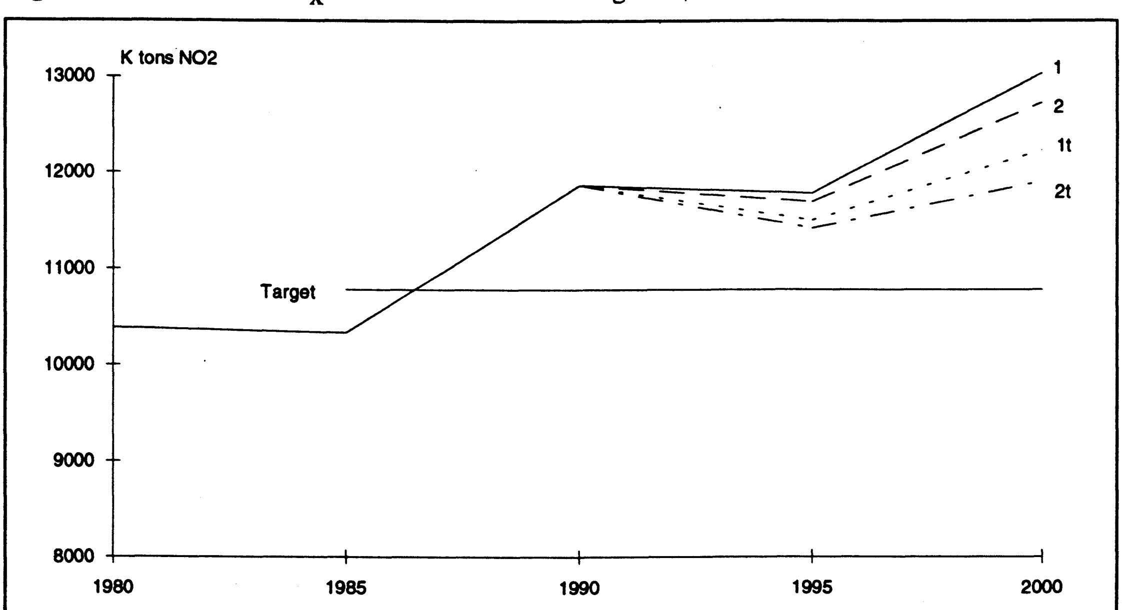
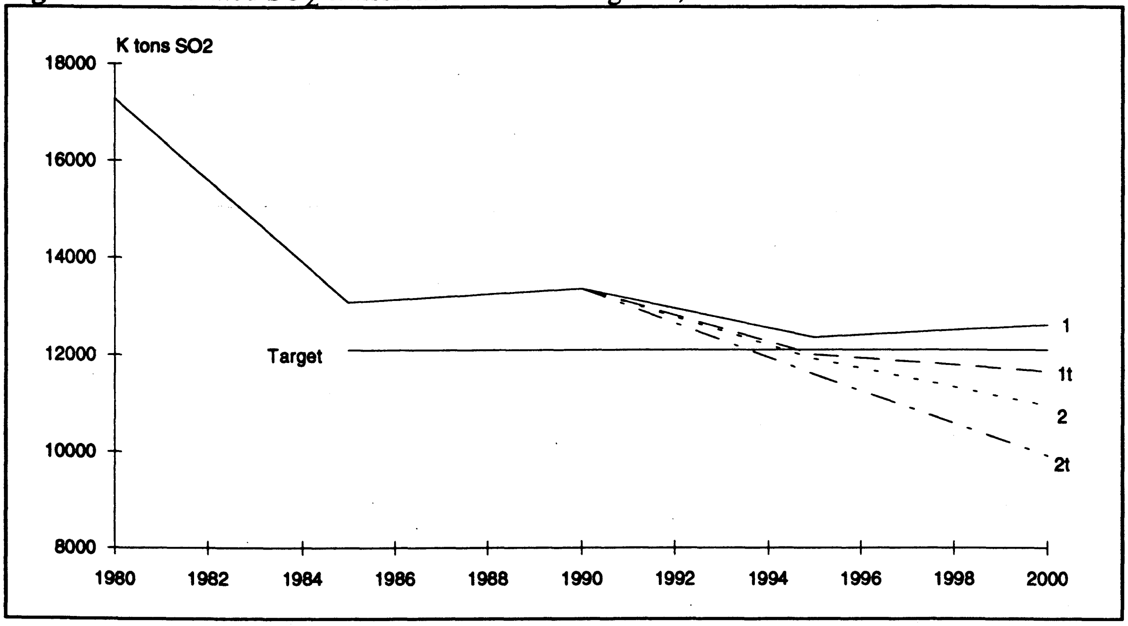


Figure 3c. Simulated SO_2 emissions under both regimes, with and without the EC tax



6. Transboundary transport and deposition

In the previous sections we have focused on the reduction in total *emission* levels. While the locations of CO_2 emissions are of little importance, this is not so for NO_x and SO_2 emissions, which cause local and regional damages to nature.

RAINS computes atmospheric long-range annual transfer and deposition of nitrogen and sulphur in Europe. Furthermore, RAINS also provides information on areas where deposition levels of sulphur exceed the "carrying capacity" of the ecosystem. The carrying capacity, usually referred to as the critical load or CL, takes into account the specific condition of the ecosystem in each location. Combining the information on depositions and critical loads gives us an opportunity to evaluate the effect of different energy scenarios on the ecosystems. To simplify the presentation, the state of the ecosystems in each country and scenario is presented as the percentage of the ecosystems that will experience depositions levels of sulphur above the critical loads. Thus, the effect of nitrogen deposition is disregarded here.

The percentage reduction in damaged area is in general expected to be smaller than the reduction in average deposition. This is due to the damage function used which generally reports a small change in the state of the ecosystem if the sulphur load remains high even after a reduction in deposition (i.e., the function is inelastic). The national average sulphur depositions are shown in table V, while table VI shows the share of damaged ecosystems and how they vary across scenarios.

The first column in table V reports the situation in the plan efficient regime without the EC carbon/energy tax (scenario 1).. The following columns report changes in average sulphur deposition as one alters the energy paths. Within the plan efficient regime there are only small differences from the carbon/energy tax between the SEEM countries. Averaged over the SEEM model area, the introduction of the tax reduces the deposition by approximately 5 per cent. This also applies to the cost efficient regime, but here the differences among the countries are somewhat larger. In particular Denmark and the Netherlands seem to get relative large reductions in sulphur depositions from the introduction of the carbon/energy tax in the cost efficient regime. A change in regime alone, i.e. without the introduction of the carbon/energy tax, leads to a reduction in deposition of almost 10 per cent within the SEEM area, that is almost a doubling of the effect of the carbon/energy tax.

On a European wide basis, a carbon/energy tax in the SEEM countries alone reduces average depositions by 2 per cent, while a deregulation of the power producing sector reduces depositions by 3 per cent.

Averaged over Europe, 40 per cent of the ecosystems experience damage in the plan efficient regime in year 2000. On the national level the shares varies from 97 per cent in Belgium to less than 2 per cent in Spain.

Under a plan efficient regime France and Finland benefit the most from the introduction of the carbon/energy tax when the benefit is measured as percentage reduction in damaged area. In the cost efficient regime Finland and UK are the countries benefitting the most with reductions in area exceeding the critical load of approximately 15 per cent. In both regimes the carbon/energy tax reduces average depositions over the SEEM area with close to 5 per cent.

On average over the whole RAINS-area the EC tax causes a reduction in damaged area of only 3 per cent. It should be noted, however, that the SEEM area contributes less than 25 per cent of the total deposited sulphur in the RAINS area in the plan efficient regime in year 2000.

Deregulating the power sector within the SEEM countries yields larger unharmed areas in most countries for a total reduction averaged over Europe of 3 per cent and an average reduction over the SEEM area of 6 per cent.

Table V. Deposition of sulphur in scenario 1 and changes in deposition between scenarios in year 2000

	Deposition in scenario 1 (g/m^2-yr)	**Changes in average deposition between scenarios (%)**			
		2 and 1	*1t and 1*	*2t and 2*	*2t and 1*
Denmark	1,4	-5	-5	-11	-15
Finland	0,7	-2	-5	-5	-7
France	1,3	-9	-8	-7	-15
Germany - West	3,6	-7	-5	-8	-15
Italy	1,8	-6	-4	-3	-9
The Netherlands	4,1	-13	-6	-11	-22
Norway	0,4	-7	-5	-5	-11
Sweden	0,6	-4	-4	-6	-9
United Kingdom	2,4	-18	-5	-4	-22
Average SEEM	*1,4*	*-9*	*-5*	*-6*	*-15*
Albania	1,4	-1	-1	-1	-2
Austria	2,7	-4	-3	-4	-8
Belgium	4,5	-9	-6	-8	-16
Bulgaria	3,0	0	0	0	-1
Czechoslovakia	4,5	-2	-1	-1	-3
Greece	1,5	0	0	-1	-1
Hungary	3,1	-1	0	-1	-2
Ireland	0,8	-7	-2	-2	-9
Luxembourg	3,1	-10	-9	-10	-19
Poland	3,5	-1	-1	-1	-3
Portugal	0,8	0	0	0	-1
Romania	2,3	0	0	0	-1
Spain	1,0	-1	-1	-1	-2
Switzerland	2,0	-7	-5	-6	-13
Turkey	1,4	0	0	0	0
Yugoslavia	2,2	-1	-1	-1	-2
Rem,European CIS	1,3	0	0	0	-1
Baltic region	1,4	-2	-2	-2	-4
Average RAINS	*1,6*	*-3*	*-2*	*-2*	*-5*

A mixed policy of deregulating the power sector and introducing carbon tax proves most effective in reducing the size of the harmed areas. Most benefited are United Kingdom, Switzerland and France who experience a reduction of 12 and 10 percentage points, respectively. At the opposite end we have the Netherlands, Luxembourg, Belgium and Norway. Despite relatively high percentage reductions in the depositions, the reductions in these countries are simply not large enough to bring the depositions down to the critical load levels. This is perhaps particular striking in the case of the Be-Ne-Lux countries who experiences rather substatial reductions in deposition, but almost no reductions in area of ecosystems axposed to deposition levels exceeding CL.

Averaged over Europe, the implementation of the EC tax in conjunction with a deregulating of the power sector reduces the area of damaged ecosystems from 40 to 38 per cent in 2000. Note, however, that the actual sulphur depositions experience a larger reduction and that the calculations do not take into account the effect of reduced nitrogen depositions.

Table VI. Area of ecosystem exposed to sulphur levels above critical load in scenario 1 and differences between scenarios in year 2000

	Percentage of ecosystem exposed to deposition levels above CL	**Changes in share of ecosystem above CL between scenarios (%)**			
		2 and 1	*1t and 1*	*2t and 2*	*2t and 1*
Denmark	53	-1	-1	-3	-4
Finland	29	-7	-15	-16	-22
France	44	-15	-14	-8	-22
Germany - West	95	-2	-1	-3	-5
Italy	29	-13	-10	-3	-15
The Netherlands	95	0	0	0	0
Norway	79	-1	-1	-1	-1
Sweden	41	-3	-4	-6	-9
United Kingdom	55	-8	-1	-14	-21
Average SEEM	*51*	*-6*	*-5*	*-6*	*-12*
Albania	6	-9	-9	-8	-16
Austria	65	-5	-2	-4	-9
Belgium	97	0	0	0	0
Bulgaria	83	0	0	0	0
Czechoslovakia	93	-1	-1	0	-1
Greece	5	0	0	-1	-1
Hungary	63	0	0	0	0
Ireland	17	-17	-17	0	-17
Luxembourg	95	0	0	0	0
Poland	94	-1	-1	-1	-2
Portugal	10	0	0	0	0
Romania	45	0	0	0	0
Spain	2	0	0	0	0
Switzerland	64	-5	-5	-11	-15
Turkey	22	0	0	0	0
Yugoslavia	34	-4	-4	-1	-5
Rem.European CIS	28	-1	-1	0	-2
Baltic region	37	0	0	0	0
Average RAINS	*40*	*-3*	*-3*	*-3*	*-6*

Table VII shows deposition of oxidised nitrogen in scenario *1* and percentage variations from from these depositions in the other scenarios. Generally, the variations are lower than the corresponding variations in sulphur depositions. This is not surprising, given that the inelastic transport sector is responsible for a larger share of the nitrogen depositions than the sulphur depositions.

Table VII. Deposition of oxidised nitrogen in scenario 1 and changes in deposition between scenarios in year 2000

	Deposition in scenario 1 (g/m^2-yr)	Changes in average deposition between scenarios (%)			
		2 and 1	*1t and 1*	*2t and 2*	*2t and 1*
Denmark	0.7	-2	-5	-5	-7
Finland	0.2	-1	-4	-4	-5
France	0.6	-2	-5	-5	-6
Germany - West	1.3	-2	-5	-6	-7
Italy	0.6	-1	-4	-4	-5
The Netherlands	1.2	-3	-5	-5	-8
Norway	0.3	-2	-4	-5	-7
Sweden	0.3	-1	-4	-5	-6
United Kingdom	0.5	-3	-5	-5	-8
Average SEEM	*0,5*	*-2*	*-5*	*-5*	*-7*
Albania	0.4	-2	-2	-2	-3
Austria	1.2	-2	-4	-5	-6
Belgium	1.2	-2	-5	-5	-7
Bulgaria	0.5	0	-1	-2	-2
Czechoslovakia	1.0	-1	-3	-4	-5
Greece	0.3	-1	-2	-1	-2
Hungary	0.7	-1	-2	-2	-3
Ireland	0.3	-2	-4	-4	-6
Luxembourg	1.3	-2	-6	-5	-7
Poland	0.8	-1	-3	-3	-4
Portugal	0.3	-1	-1	-1	-2
Romania	0.5	0	-1	-1	-1
Spain	0.3	-1	-1	-1	-2
Switzerland	1.1	-1	-5	-5	-6
Turkey	0.3	0	0	0	0
Yugoslavia	0.6	-1	-3	-3	-4
Rem,European CIS	0.3	0	-1	-1	-2
Baltic region	0.5	-1	-3	-3	-4
Average RAINS	*0.4*	*-1*	*-1*	*-3*	*-4*

7. Effects on abatement costs

RAINS provides national cost curves expressing the relationship between marginal abatement costs, total control costs, and the emission levels of SO_2 and NO_x. These costs are technological costs and do not include costs associated with energy substitution or conservation, or economic activity. It is assumed that emissions are first abated where the marginal cost is lowest. These curves, therefore, indicate the most cost-effective means of reducing emissions within a given country. Because of structural differences in energy consumption and fuel quality, the control costs vary considerably among countries. As shown above, the EC tax will change the structural energy demand. It is thus also of interest to see how it will affect the national abatement costs. We start by showing the effect on an aggregated level by constructing, from single country data, the marginal cost curves for the total SEEM area. Each point on the aggregated marginal cost curve corresponds to identical marginal abatement cost in each country and the corresponding sum of emissions in the SEEM area. Analogous to the national cost curves, the aggregated marginal cost curves show the most cost-effective means of reducing emissions within the SEEM area.[7]

In figure 4a-b we have plotted the emissions and marginal costs for all four scenarios for the NO_X and SO_2 emissions, respectively. Marginal costs are equal to zero at the emission levels in year 2000. As the marginal cost increases, more abatement techniques are being utilised and the emissions consequently fall.

Figure 4a. Marginal NO_X abatement costs in the SEEM area. Year 2000

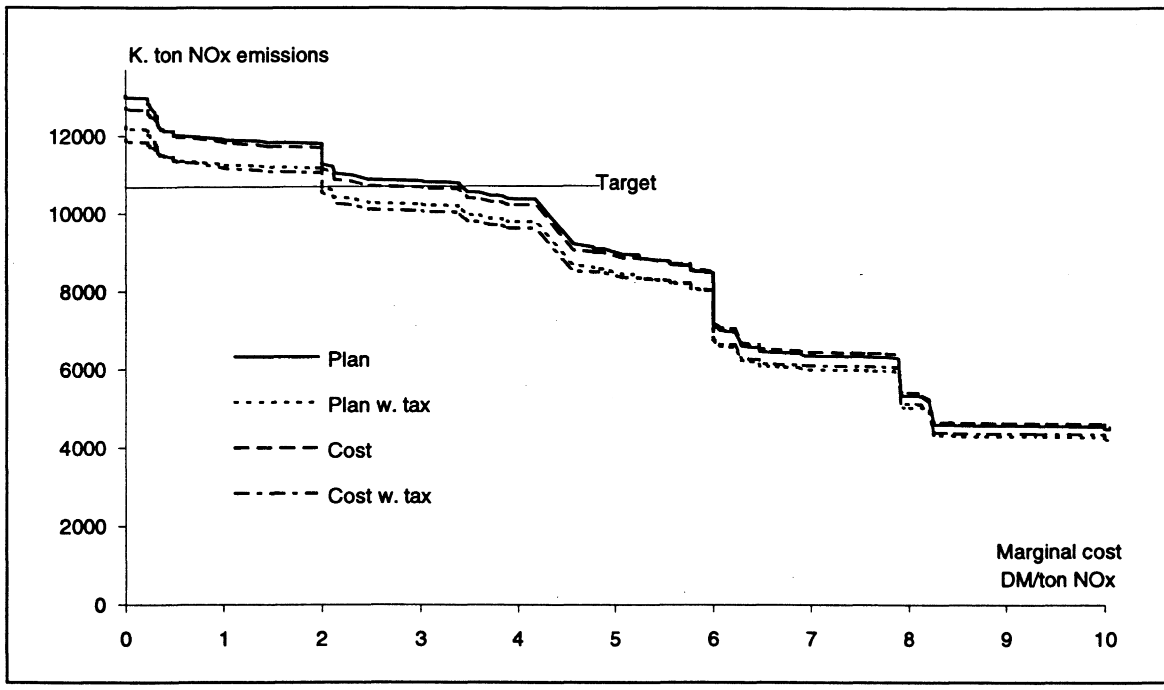


Figure 4a indicates that the abatement costs for NO_X are relative inelastic as soon as the cheapest techniques are exhausted. This leads to large discrepancies between the marginal abatement costs in the various scenarios. For instance stabilisation at the 1987 level has a marginal abatement cost of 3,8 DM per ton NO_X in scenario 1 compared to 3,4 DM in scenario 2. Introduction of the EC tax reduces the marginal cost at which the Sophia protocol is met considerably; to 2,5 - 3,0 DM per ton NO_X. Total costs, given as the area between the cost curves and the line depicting the Sophia protocol, are reduced even more. To meet the protocol in the non-tax scenarios (1 and 2) costs approximately 3 691 and 3 137

[7]Cost effectiveness in this context is limited to minimisation of the total abatement cost. Benefits from the abatement are not taken into account.

million DM per year in the plan and cost efficient regime, respectively. The corresponding numbers for the tax scenarios (1t and 2t) are 1 461 and 1 052 million DM. The large reductions of the total abatement costs caused by the EC tax is of course due to the fact that one does not have to apply the most costly control techniques in the tax scenarios.

Figure 4b. Marginal SO_2 abatement costs in the SEEM area. Year 2000

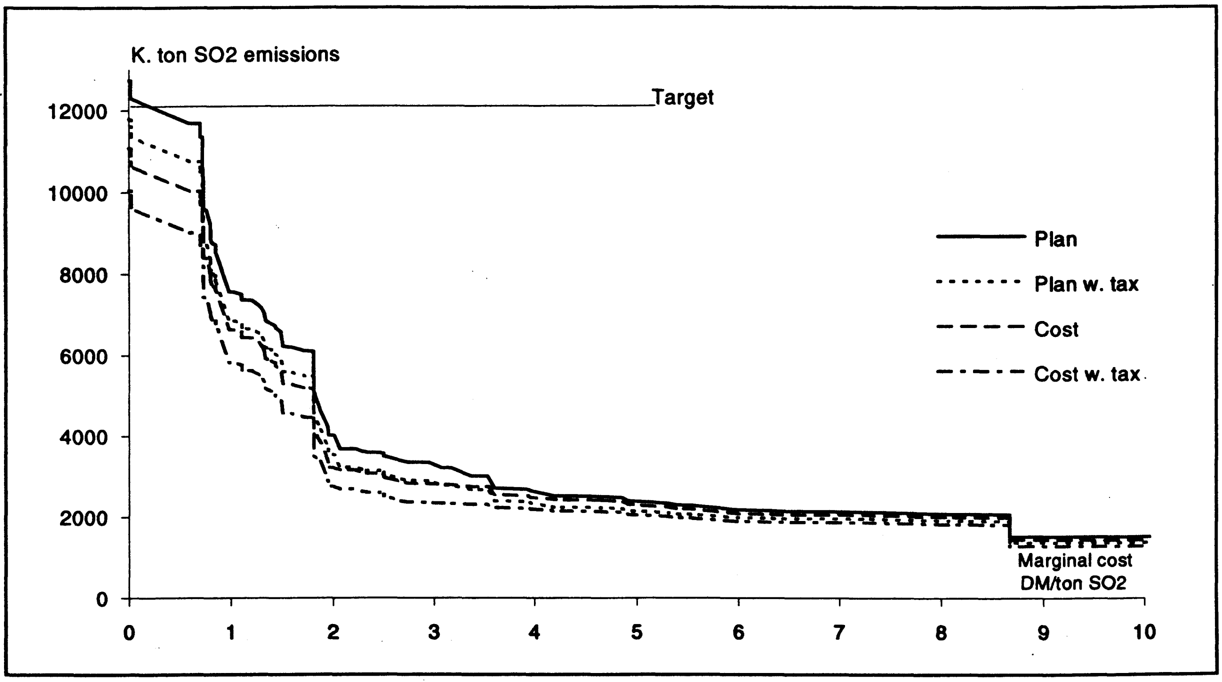


Figure 4b suggests that the SO_2 abatement is far more elastic with respect to marginal costs than NO_x abatement. As described earlier the SO_2 emissions barely exceed the target of 30 per cent reduction in the plan efficient regime without tax. The marginal cost which is necessary to meet the protocol is thus only 0,4 DM per ton SO_2.

To show the effects of national emissions and cost differences we present an overview of the distribution of abatement cost between countries for a specific abatement scenario. The chosen scenario, which only serves as an illustration, is designed such that all countries individually, and thus the model area as a whole, meet the Sophia and Helsinki protocol in year 2000.

Table VIII and IX shows the annual control costs for NO_x and SO_2 measured in million 1985-DM per kiloton SO_2 and NO_x removed.

Table VIII. Annual control costs to meet the Sophia protocol. 2000. Million 1985-DM per ton NO_2.

	Scenario 1	**Scenario 1t**	**Scenario 2**	**Scenario 2t**
Germany (west)	1,2	0,5	1,2	0,5
United Kingdom	2,0	1,3	2,2	1,5
France	2,8	2,1	2,9	2,1
Italy	1,1	0,4	1,0	0,4
Netherlands	1,0	0,5	0,9	0,4
Sweden	0,2	0,0	0,0	0,0
Denmark	0,2	0,0	0,3	0,0
Finland	0,4	0,0	0,4	0,0
Norway	5,2	4,9	5,2	4,9
Total	*1,9*	*1,3*	*2,0*	*1,5*
Cost minimising scheme	1,6	1,0	1,6	0,9

Table VIII reveals large differences in the national abatement costs for NO_x. This is not surprising since the national abatement cost depend on the required reduction to meet the national goal, elasticity of the marginal cost curve and, in the policy scenarios, the flexibility of the energy system in each country. For instance, to reach the required reductions in the plan efficient regime is almost twice as expensive per ton NO_x in Norway compared to the second most expensive country, France. Sweden and Denmark almost fulfil the Sophia protocol in the plan efficient regime in year 2000 thus and have only negligible abatement costs in the non tax scenarios.

Deregulation of the power sector has only a modest impact on the NO_x abatement costs. The EC carbon/energy tax on the other hand greatly affects the total abatement costs. Least benefited, in terms of relative change, are Norway and France with their steep abatement costs, high required emissions reductions and relatively small tax induced emission reductions. All the Nordic countries except Norway would in the case of an EC tax under a flat rate abatement regime fulfil the NO_x protocol which implies zero control costs. The annual NO_x abatement costs for the SEEM area as a whole is reduced by 60 and 71 per cent in the plan and cost efficient regime, respectively, under an EC tax.

The bottom line of the table shows the total cost of abatement under the Sophia protocol if each country abate according to the marginal abatement cost depicted in figure 4a. The simulation clearly suggests that there are substantial savings to be had by avoiding flat rate protocols on emissions. Furthermore, the EC tax would increase the saved amount. Countries with high emissions, inelastic marginal abatement cost curves and little flexibility in their energy structure, such as Norway, France and United-Kingdom, could benefit from other countries' more advantageous control conditions. The lowest control cost for NO_x is achieved by distributing the emissions reduction such that marginal control costs are equal in a cost efficient regime with a carbon/energy tax. Such a policy would reduce the control cost by 35 per cent compared to the flat rate.

Table IX reveal large differences in the national abatement costs for SO_2 too. Not surprisingly we find the highest average abatement costs in the coal countries Germany (west) and United Kingdom. Deregulation of the power sector yields emissions in United Kingdom and the Netherlands below the national flat rate targets. Along with large reduction in Germany (west), the result is a 85 per cent drop in the total control costs.

Table IX. Annual control costs to meet the Helsinki protocol on a flat rate basis. 2000. Million 1985-DM per ton SO_2

	Scenario 1	**Scenario 1t**	**Scenario 2**	**Scenario 2t**
Germany (west)	1,0	0,8	0,8	0,0
United Kingdom	0,7	0,7	0,0	0,0
France	0,0	0,0	0,0	0,0
Italy	0,0	0,0	0,0	0,0
Netherlands	0,7	0,6	0,0	0,0
Sweden	0,0	0,0	0,0	0,0
Denmark	0,0	0,0	0,0	0,0
Finland	0,6	0,6	0,6	0,5
Norway	0,0	0,0	0,0	0,0
Total	*0,8*	*0,7*	*0,7*	*0,5*
Cost minimising scheme	0,3	0,0	0,0	0,0

As in the case of NO_x, the EC carbon/energy tax has a large impact on the total SO_2 abatement costs, 45 and 80 per cent reduction in the plan and cost efficient regime, respectively. Least benefited is Finland which is the sole country left with control costs in the cost efficient regime with EC tax. The other countries have through the implementation of EC tax and/or deregulation of the power sector reduced their emissions below required national reduction to meet the Helsinki protocol on a flat rate basis.

8. Conclusions

The simulations presented above clearly indicate that CO_2 abatement in Western Europe is not only a matter of the level of taxation. On the contrary, the efficiency of a uniform tax as proposed by the EC Commission depends crucially on the investment behaviour of the government controlled power producers. *Status quo* of the national regimes, here denoted as the plan efficient regime, means that the efficiency of taxation is significantly reduced. Nevertheless, the simulations indicate that the tax is sufficient to stabilise CO_2 emissions by year 2000 even in the plan efficient regime. However, cost efficient investment decisions in the thermal power sector enhances the potential effect of a carbon tax and postpones the point in time where a carbon tax has to be raised to meet the stabilisation target after the turn of the century.

Our analysis shows that an economic instrument for controlling CO_2 emissions has a sizeable impact on the emissions and depositions of NO_X and SO_2. Abatement costs incurred by traditional cleaning technologies are also affected by the carbon/energy tax. The linkage of SEEM and RAINS illustrates that efficient use of an economic instrument for controlling one polluting component requires that its effect on other polluting components is taken into account. This calls for coherent and synchronised negotiation, planning and implementation of economic instruments for air polluting control.

Finally, we note that not covered by this study are the secondary benefits of a carbon/energy tax associated with reductions in pollution induced health damage and damage to nature and man made materials. External effects of road traffic are also sensitive to the pricing of transport oils. Tentative calculations for Norway indicate that the benefits of reduced health damage from NO_X emissions and reduced congestion and accidents, etc. on roads, goes a long way toward mitigating the direct costs of a carbon/energy tax, see Alfsen et al. (1992).

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