

Future uses of fossil fuels: A global view of related emissions and depositions

W. HÄFELE¹, H. RIEMER¹, J. H. AUSUBEL² and H. GEIß¹

¹Kernforschungsanlage Jülich GmbH, Postfach 1913, D-5170 Jülich, Federal Republic of Germany,

²National Academy of Engineering, Washington, D.C., U.S.A.

(Received 15 October 1985; accepted 16 April 1986)

Abstract—The flow of fossil fuels through contemporary civilizations, and the related emissions and depositions of sulphur and nitrogen compounds, can no longer be considered to be of only local importance. The size of these flows compares with and even exceeds natural cycles. This leads to a problem whose future evolution in time is not clear. The question becomes more difficult with the present tendency to increase use of fossil fuels. Whereas this was considered a problem of the quantity of available resources in the 1970's, it may now turn out to be a problem of the quality of resources.

The procedure applied in the present study highlights the lack of data and knowledge. Particularly striking are lack of data on quality of resources, the chemistry of the atmosphere, and the transport of aerosols, and the lack of standards by which to judge effects of NO_x and SO₂ deposition.

Key words: energy uses, fossil fuels, environment, emission, deposition, sulphur, nitrogen

THE COMPLEX OF ENVIRONMENTAL EFFECTS

Issues surrounding the emission of atmospheric pollutants at the regional and global scale have grown increasingly complex. In the past, the emission of carbon dioxide from combustion of fossil fuels has been strongly emphasized (see, for example, Carbon Dioxide Assessment Committee (1983), Ramanathan *et al.* (1985) or Dickinson and Cicerone (1986). In going from 1980 to the year 2030, Ramanathan *et al.* has envisaged an increase in CO₂ concentration in the atmosphere from 339 to 450 ppm (Table 1). This is likely to happen and, in fact, hardly possible to avoid, although the date may be postponed a decade or two. It is only recently that other compounds have been considered carefully (Table 1). For example, nitrogen and sulphur compounds, the main sources of acid

deposition, have important anthropogenic as well as natural sources. Additional anthropogenic emissions include ozone, methane, and chlorofluorocarbons. Quantitatively the emissions do not always seem impressive compared to the volume of the atmosphere. However, though quantities of emissions may be small, they represent an absolute increase, which can sometimes be significant and surprisingly powerful.

The consequence of increased concentrations of CO₂ and all the other so-called trace gases is increased surface warming due to the greenhouse effect. Ramanathan *et al.* (1985) and Dickinson and Cicerone (1986) give a striking estimate of the cumulative global change. Looking at the warming process historically from the preindustrial concentration level (about 275 ppm for CO₂), there is a temperature increase of 0.5 K up to the year 1980. To the present, all the other trace gases may have enhanced the CO₂ value by 50%. From 1980 to 2030 the expected

Opening lecture to the 12th International Meeting on Organic Geochemistry.

Table 1. Estimates of the abundance of trace chemicals in the global atmosphere of 1980 and 2030 (Ramanathan *et al.*, 1985).

Chemical group	Dominant source N = Natural A = Anthropogenic	Year 1980 Global average mixing ratio [ppb]	Year 2030 Probable global average concentration [ppb]
Carbon dioxide CO ₂	N, A	339 · 10 ³	450 · 10 ³
Nitrogen compounds e.g. N ₂ O	N, A	300	375
Sulphur compounds e.g. SO ₂	N, A	0.1	0.1
Fully Fluorinated species e.g. CF ₄	A	0.07	0.24
Chlorofluorocarbons e.g. CCl ₃ F (F11)	A	0.18	1.1
Chlorocarbons e.g. CH ₃ CCl ₃	A	0.14	1.5
Others: Ozone, Brominated Species, Hydrocarbons, Aldehydes			

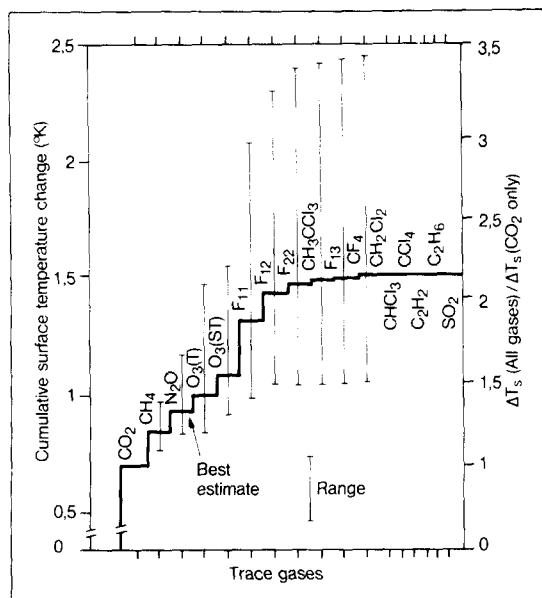


Fig. 1. Cumulative equilibrium surface temperature warming due to increase in CO_2 and other trace gases. Increases in concentration of trace gases in the atmosphere from 1980 to 2030 (Ramanathan *et al.*, 1985).

temperature increase is 0.7 K due to CO_2 emissions and 1.5 K due to all greenhouse gases (Fig. 1). This implies an effect of 110% from trace gases projected to increase at the same time as CO_2 emissions. Many of the compounds are not related to energy production. So we do have a very complex situation.

This paper will concentrate on emissions associated with energy, principally to use it as a paradigm, because the interactions are rather well identified. We develop particular cases for the year 2030 and compare them with the current situation, social goals, and technical possibilities. It is anticipated that such studies can be extended to areas other than fossil fuel use. The need to consider geochemical mass flows in their totality will become clear.

PICTURE OF A FUTURE: THE IIASA-LOW-SCENARIO

It is impossible to predict future levels of use of energy and fossil fuels with a high degree of certainty. We have learned with great pain that the most we can do is to consider scenarios, that is, to make consistent pictures of a possible future, but not of *the* future. The drawing of a rather detailed picture forces us to make assumptions, and these assumptions have to be defined in a scientifically rigorous way. One can then consider a range of estimates in a meaningful fashion. This has been done in the extensive study *Energy in a Finite World* by Häfele *et al.* (1981).

In recent years with regard to envisaged futures, there has been a remarkable coincidence among the expectations of various groups: the Shell Group, J. H. Lichtblau (Mineral Research Institute of New York), the World Energy Conference 1983

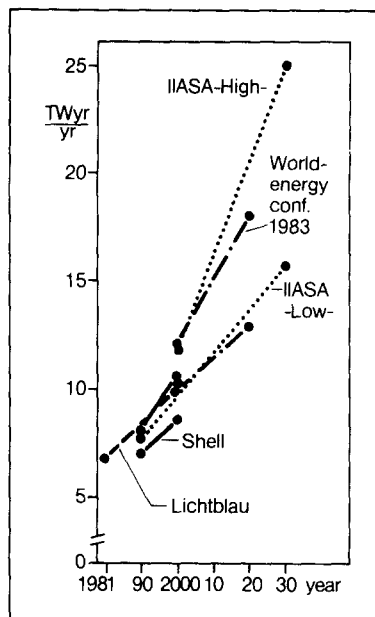


Fig. 2. Expected increase of the World energy consumption from 1981 to 2030 according to Häfele *et al.* (1981) for IIASA-Low and IIASA-High, Lichtblau (1983), Deutsche Shell Aktiengesellschaft (1982) and 12th World Energy Conference (1983) in terawatt-year per year (TWyr/yr).

(low estimate), and the so-called IIASA-low-scenario (Fig. 2). That means there is a meeting of minds, but not necessarily an assurance about the future. These various observers can be collectively wrong.

The IIASA-low-scenario, which coincides well with the others, envisages a total of 15–16 TWyr/yr by the year 2030. (Total energy consumption in the world today is on the order of 8 TWyr/yr.) The scenario assumes a global population increase from 4 billion people in 1975 to 8 billion in 2030 (Table 2). In the countries of the Organization for Economic Co-operation and Development (OECD) a doubling to tripling of the Gross Domestic Product (GDP) is

Table 2. Basic data from the IIASA-low-scenario (Häfele, 1981). GDP: Gross Domestic Product; OECD: Organisation for Economic Co-operation and Development; Comecon: Soviet Union and Eastern Europe; LDC: Less Developed Countries.

	1975	2030
● World population [10^9]	4	8
● GDP per capita [US \$ 1975]:		
– OECD:	5088	13202
– Comecon:	2562	9820
– LDC:	464	1177
● Primary commercial energy consumption per capita [kW/cap]:		
– OECD:	6.2	8.2
– Comecon:	5.0	10.4
– LDC:	0.43	1.3

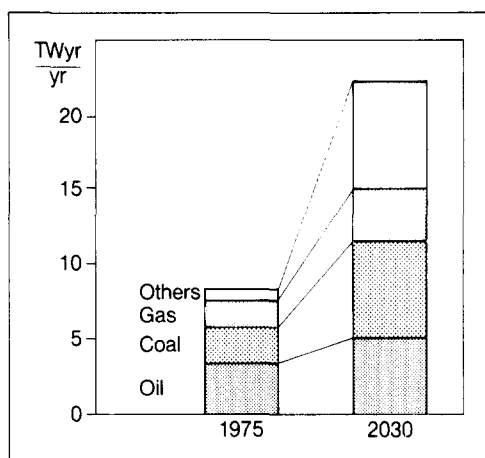


Fig. 3. Primary energy consumption of the World for 1975 and 2030 according to the IIASA-low-scenario (Häfele *et al.*, 1981). Category "Others" includes nuclear energy, renewable energy and energy from hydro power. Values in terawatt-year per year (TWyr/yr).

estimated. In the Soviet Union and Eastern Europe (COMECON) there will be a tripling, and in the less developed countries (LDCs) perhaps a twofold increase in GDP.

Increase in primary energy consumption will be less significant, because in the scenario a strong role for energy conservation is assumed. Energy is always a political affair—at least it used to be—and in some ways a religious one, as well. There are religious positions on the role of energy conservation, for example. For this reason, it should be mentioned explicitly that a large amount of energy saving is envisaged—but not an amount of energy saving that may satisfy the doctrines of all groups in the energy debate. Primary energy consumption of the world will increase between 1975 and 2030 (Fig. 3) because consumption of all energy carriers is increasing, not decreasing as some have predicted. Along with fossil fuels, the current and projected increase should be noted particularly for nuclear energy.

The source of about 25% of total consumption of primary energy in 2030 is expected to be nuclear energy (Fig. 4). The share supplied by gas will remain constant between 1975 and 2030. The relative share for oil will decrease in that period, although the absolute amount of oil consumed will increase somewhat. The relative share of oil decreases in this scenario because a certain share of coal will go into liquefaction. Consequently, the use of coal will shift from electricity generation to other, noncombustive uses. That amount will then essentially be replaced by nuclear energy—at first by light-water reactors, later by fastbreeder reactors.

APPROACH TO THE PROBLEM

The results of this study have to be considered under certain general assumptions. The first assumption

is that the IIASA-low-scenario is applicable. While it might be desirable to employ a new scenario, it takes several—say 10 or 20—man-years to develop one, and such an effort seems unreasonable unless results from this more economical approach are compelling.

The applicability of the IIASA-low-scenario implies in particular:

- a modest economic growth rate for the world as a whole (2%)
- a significant amount of energy saving (consequently, the even more modest energy growth rate); and
- one quarter of primary energy comes from nuclear energy in the year 2030.

The next important assumption is that the technological level of the capital stock that existed at the end of the 1970's would continue to be used. This means that technology is not providing widespread abatement measures for smokestacks and cars. This assumption is intended to provide a reference point against which the necessity of abatement measures can be judged.

Moreover, two cases of fossil fuel quality for 2030 are considered:

- a constant quality, namely that of 1975; and
- a degradation in quality of 50% in sulphur content for coal and oil and a decrease of 25% in calorific value.

Bulgaria, for instance, currently uses lignite with a calorific value of 1400 kcal/kg, while the Federal Republic of Germany uses lignite of about twice that quality—2500–3000 kcal/kg. The Bulgarians are preparing to use lignite of a quality of only 900 kcal/kg, and the F.R.G. is also expecting to use lower grade resources. These are just examples, but exhaustion of higher quality resource is certainly a problem for Eastern Europe, the Soviet Union, and some other countries, including Brazil, India, and China.

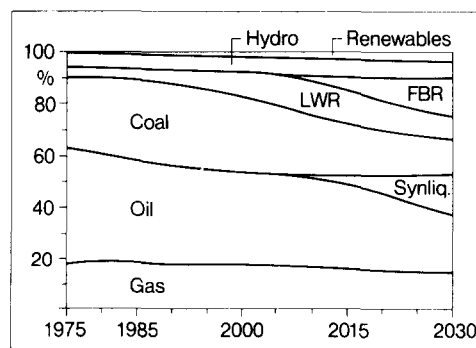


Fig. 4. Evolution of primary energy shares by source from 1975 to 2030 according to the IIASA-low-scenario (Häfele *et al.*, 1981). LWR: Light water reactor; FBR: Fast breeder reactor; Hydro: Hydropower; Synliq.: Synliquids from coal gasification.

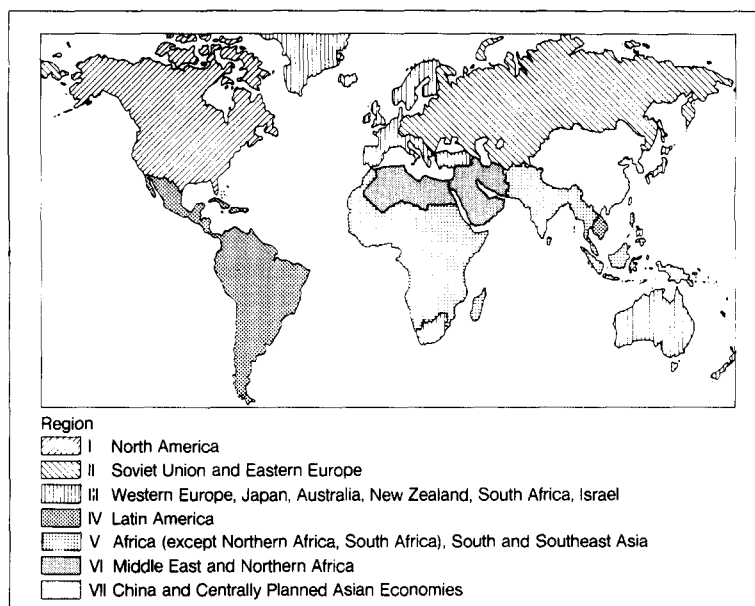


Fig. 5. The IIASA-World-regions (Häfele *et al.*, 1981).

One essential assumption is that institutional arrangements can be made to produce a prudent allocation of primary fuels to energy users. The aim would be to distribute the various primary fuels in a way that helps minimize emissions. In practice, such a minimization would be accompanied by improved technology. But in order to have a benchmark against which to judge the necessity of improved technologies, we have assumed that more prudent allocation does not happen automatically.

The approach to the general problem of emissions also had to be influenced by the fact that for many aspects appropriate data are not available. It was thus decided to reduce the general complexity of industrial emissions to the case of energy, to limit the energy case to fossil fuels, and then to consider only the emission of sulphur and nitrogen compounds. An extension to consideration of heavy metals and organic emissions is clearly desirable but difficult because of lack of data.

Adopting the time horizon of the IIASA-low-scenario, we consider the evolution of emissions and depositions to the year 2030. The spatial frame is essentially based on the set of seven IIASA world regions, which were defined in view of economic, political, and trade considerations Häfele, 1981) (Fig. 5). Region I, North America, may be characterized as a developed market society rich in resources. Region II, the Soviet Union and Eastern Europe has a developed, centrally planned economy and is also rich in resources. Region III, essentially the OECD member countries minus North America, has a developed market economy and not many resources. Region IV, Latin America, is a developing region with market economics and many resources. Region V, Africa and South and Southeast Asia, is

also a developing region, with mostly market economies but not many resources. The countries of the Middle East and Northern Africa, Region VI, are a special case with their rich oil and gas resources. Finally, Region VII, China and the centrally planned Asian economies, is a developing region with centrally planned economies, and it is not so favored in resources.

Although the IIASA-low-scenario permits us to make statements on all world energy regions, here we concentrate on Regions I, II, and, with a modification, on III. In a more extended report on this issue, all regions are investigated (Häfele *et al.*, 1986). While emissions can be calculated according to IIASA regions, depositions have to be calculated geographically. The modification of Region III is introduced because this IIASA Region is not geographically coherent. So we restrict ourselves mostly when depositions are calculated for Europe and do not present in these cases findings for the other parts of Region III, i.e. Japan, Australia, New Zealand, South Africa and Israel.

PROCEDURE: EMISSIONS TO DEPOSITION

Emitted sulphur dioxide is removed from the atmosphere through three important processes:

- deposition on surfaces
- formation of sulfate aerosol following atmospheric oxidation to H_2SO_4
- absorption and oxidation in cloud water.

Emissions of SO_2 may return to the land or the sea as dry depositions of SO_2 (Fig. 6, Kley, 1985) but may also be converted to SO_4 (Iranov and Freney, 1983; Bolin and Cook, 1983; Stockwell and Calvert, 1983).

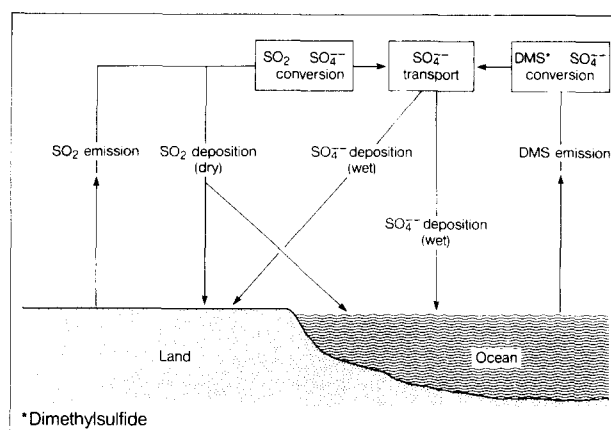


Fig. 6. Major fluxes in the atmospheric cycle of SO_2 (Kley, 1985).

If there is a long pathway from emission to deposition, the opportunity for photochemistry to facilitate this conversion is great. Then the SO_4 compounds come down as wet deposition. This process probably occurs in the case of tall stacks, and one can therefore not be sure that the policy of tall stacks has a beneficial effect, as wet deposition of SO_4 is most likely harmful.

The atmospheric cycle of nitrogen is much more complex than that of sulphur. Kley (1985) has described its essentials in Fig. 7. Nitrogen oxides, NO_x , may be either anthropogenic, as in stratospheric intrusion, or natural, as in atmospheric generation of NO_x by lightning. The conversion product in the atmosphere is designated NO_y . Here too, conversion will take place during the transport, and again dry and wet deposition have to be considered. Dry deposition of reactive nitrogen is mostly as HNO_3 , wet deposition is mostly NO_3^- . Nitrate (NO_3^-) is thought to come mainly from incorporation of HNO_3 in

precipitation. Actually, in a more thorough analysis one has also to take the emissions of NH_3 from coal combustion into account. This has been estimated world-wide to be at $4\text{--}12 \cdot 10^6 \text{ tN/yr}$ (Söderlund and Svensson, 1976) while the total nitrogen emissions through the anthropogenic NO_x route is at $40 \cdot 10^6 \text{ tN/yr}$ (1975). For the purposes of providing just orientations considered here, the emission of nitrogen through the NH_3 route may be neglected.

In the case of nitrogen emissions, a major feedback to the agricultural sector needs to be elaborated. Future activities of the Nuclear Research Center (KFA) at Jülich will include study of the nitrogen cycle, with particular attention to the interconnections to agriculture.

To calculate emissions, one has to disaggregate the consumption of fossil fuels into coal, gas, and oil in various sectors, including household/service, industry, transportation, electricity generation, and coal gasification. IIASA publications facilitate these

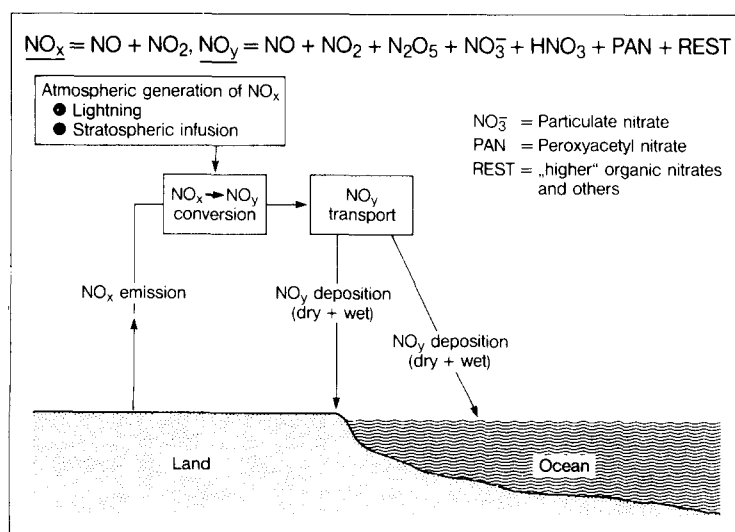


Fig. 7. Major fluxes in the atmospheric cycle of NO_x (Kley, 1985).

Table 3. SO₂- and NO_x-emission factors for coal, gas and oil depending on their usage for the Federal Republic of Germany in 1975. The emission factor indicates the amount of pollutants per unit energy used in gigawatt-year (GWyr)

		Household Service	Industry	Transportation	Electricity Generation
SO ₂ * 10 ³ t S/GWyr	Coal	5.9	9.85	9.85	13.65
	Gas	0.03	0.16	–	0.16
	Oil	2.85	10.15	1.95	14.2
NO _x * 10 ³ t N/GWyr	Coal	0.81	3.47	3.47	6.3
	Gas	0.72	1.44	–	2.7
	Oil	0.72	2.16	7.79	3.42

*Values reported refer to the abundances of elemental sulphur and nitrogen and not to those of SO₂ and NO_x.

allocations for all regions based on the IIASA-low-scenario (Balabanov *et al.*, 1982; Chant, 1981; Häfele, 1981; Khan and Holzl, 1982). To calculate deposition requires a further disaggregation within regions on a country-by-country basis (United Nations, 1981; Statistical Office of the European Communities, 1976). The needs here for calculation differ from that for greenhouse gases, which affect the physics of the atmosphere at a global level. To explore questions of acid deposition, more data are necessary to describe the emission problems in their full complexity.

As a simplified approach, a classification scheme was defined to accommodate, on the one hand, the sparse data and, on the other hand, the large amount of work to be carried out for each country. Matrices of emission factors for 1975 and 2030 were elaborated for each country in each IIASA region for nitrogen and sulphur based on estimates of quality of fossil fuels. As an example, the matrix for the Federal Republic of Germany is given in Table 3. The values are based on publications from Garnreiter *et al.* (1983), Allhorn *et al.* (1984), and private communications with Huber and Niessen at the Nuclear Research Center of Jülich.

While the IIASA scenario gives a consistent picture of future allocation of energy consumption for the

designated world regions, it does not address variations from the present for each country within this region. Therefore, it was assumed that there will be no significant change from 1975 to 2030 in the shares of energy consumption among the countries of a region.

With this framework, the emission for a pollutant is calculated from the following equations:

$$S'_{k,e,i} = \gamma'_{k,e,m} \cdot \alpha_{k,e,i} \cdot E'_{k,e} \text{ [10}^6 \text{ t/yr]}$$

and

$$S'_{k,e} = \sum_i S'_{k,e,i} \text{ [10}^6 \text{ t/yr]}$$

where

$\gamma'_{k,e,m}$ = emission factor for a particular pollutant in energy sector k for energy carrier e of country category m at time t (= 1975 or 2030) 10³ t/GWyr

$\alpha_{k,e,i}$ = share of energy carrier e in energy sector k and in country i of the considered IIASA region

$E'_{k,e}$ = energy consumption of the energy carrier e in sector k at time t (= 1975 or 2030) of the considered IIASA region.

For all of IIASA Region III, Table 4 shows the calculated SO₂ and NO_x emissions in 1975. The

Table 4. Allocation of the calculated amounts of SO₂ and NO_x emitted in 1975 for the IIASA-region III (for definition see Fig. 5) and their allocation to emission heights.

		Household/ Service	Industry	Transportation	Electricity Generation	Total
SO ₂ *	Coal	0.27	1.99	0.25	4.60	7.11
	Gas	0.01	0.02	0.00	0.01	0.04
	Oil	0.76	3.56	0.56	3.71	8.59
	Total	1.04	5.56	0.81	8.31	15.74
NO _x *	Coal	0.04	0.70	0.09	2.12	2.95
	Gas	0.06	0.12	0.00	0.11	0.29
	Oil	0.19	0.76	2.21	0.90	4.06
	Total	0.29	1.58	2.30	3.13	7.30
Emission height [m]		30	100	30	350	

*See footnote in Table 3.

Table 5. Comparison of different estimates of the amounts of SO₂ and NO_x emitted in 1975 (or 1978) with own estimates for main countries or regions.

	Nat. Research Council, Washingt. 1981	Report of the Prime Minister to the Parl. London 1985	Environmental Protection Agency, Washingt. 1985	Norwegian Meteorological Institute, Oslo 1985	Own Estimate
SO ₂ * [10 ⁶ t S/yr]					
USA	13	13.5	14.5	-	10.5
IIASA Region II	-	-	-	15 (1978)	15
East Europe	-	-	-	7 (1978)	6
West Europe	-	-	-	13.5 (1978)	11.5
U.K.	-	2.6	-	2.6 (1978)	2.6
FRG	-	1.8	-	1.8 (1978)	2.1
France	-	1.6	-	1.8 (1978)	1.6
NO _x * [10 ⁶ t N/yr]					
USA	8.6	9	9	-	8.1
U.K.	-	0.8	-	-	1.2
FRG	-	1.3	-	-	1.1
France	-	0.6	-	-	0.7

*See footnote in Table 3.

allocation of the consumption of fossil fuel turns out to be critical for the total emission and therefore for the related deposition. Table 4 shows that a total of $16 \cdot 10^6$ tS were emitted as SO₂ in 1975 and that more than half of the SO₂ emissions came from electricity generation; industry also had a significant share. It is enlightening to see the relative shares of various fuels, for instance, the small amounts of gas consumption in all sectors, and to see the relatively large role that electricity generation plays in total SO₂ emissions. Most of the $7.5 \cdot 10^6$ tN calculated to have been emitted in 1975 as NO_x came from transportation and electricity generation. Only coal and oil for industrial purposes accounted for significant additional emissions of NO_x.

In answer to the question "how accurate is our approach?" we compared our calculations for 1975 with a set of other sources employing different methods (Table 5). Considering that the intent of our effort is to pose broad questions about possible developments, the coincidence is relatively satisfactory, even on a country basis. Thus, we proceed to the next state of calculations.

Bearing in mind that we just wanted to provide an orientation for the future development of depositions caused by the emissions of fossil fuels, we looked at the large-scale geographical situation and its change. We did not lay claim to a forecast of the level of pollution in detail.

Therefore, to address the problem of deposition we used a meteorological approach which is based on a Gaussian plume model for the dispersion of pollutants following the approach of Pasquill (1974). For distances ranging up to 100 km this is for the purposes considered here a good enough approximation and follows a widely used procedure. It is recognized that for long distances, very high stack heights, and special topographical conditions one has to improve the Pasquill approach when more specific and precise problems are to be dealt with.

The model used for our purposes calculates mean values of air concentration, dry and wet deposition over a period of one year or more. It takes into account a 3-dimensional meteorological statistic including wind direction, wind speed, and atmospheric stability classes. This statistic represents an average over a period of ten years and a set of 25 meteorological stations in the Federal Republic of Germany. It is obvious that within the west wind region between the 30th and 60th latitude there are no great differences for the averaged wind speed and wind direction frequency distribution, e.g. for Berlin and Paris.

To calculate wet deposition we assume a spatial and temporal constant precipitation.

In detail the model describes the dry and wet deposition according to Chamberlain (1953) and Chamberlain and Chadwick (1953). We assume that the dry deposited material is proportional to the concentration in the air near the ground. The amount of pollutants deposited by rain is proportional to the vertical integrated concentration pattern.

The calculations are done with proportional numbers called deposition velocity and washout coefficient.

The removal of material from the atmosphere by dry and wet deposition is calculated by a so-called source depletion factor. The depletion factor describes an exponential decrease of the pollutants dependent on source distance.

It was assumed that the calculated emissions are distributed by point sources. This implies essentially that emissions of pollutant in a given country are distributed in relation to the population density of that country. For this study we define each locale with more than 100,000 inhabitants as a point source.

The results of the model calculations were compared qualitatively with the results of other authors, e.g. Hordijk (1985). Unless treatment of emission and meteorological input differs in a strong manner, the

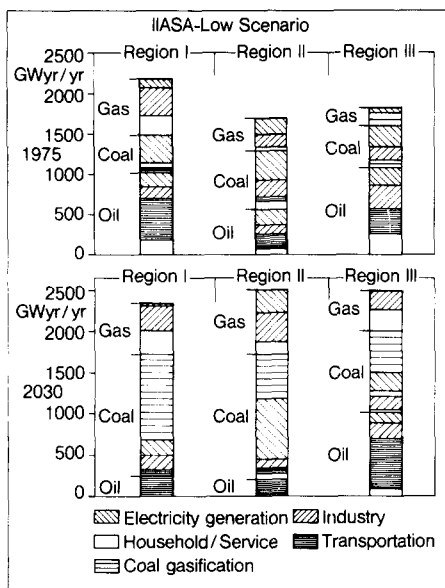


Fig. 8. Calculated amounts of fossil fuels consumed in 1975 and 2030 for selected IIASA-regions (for definition see Fig. 5) according to the IIASA-low-scenario (Häfele *et al.*, 1981; Balabanov *et al.*, 1982; Khan and Holz, 1982; Chant, 1981).

results agree within a factor of two. With our model the deposition for long distance from the pollutants would be underestimated. This is due to over-estimation of depletion up to distances of 1000 km.

We consider three emission heights at each point source:

- 30 m: household/service and transportation
- 100 m: industry
- 350 m: electricity generation and coal gasification

These values, which include a superelevation of the stacks to reflect heat emission, are often mentioned in the literature (e.g. Garnreiter, 1984; Brauer, 1984; Lahmann, 1984) and are taken as input data for the reference case of our scenario. They were varied in a sensitivity analysis and have a significant influence on deposition structure (Häfele *et al.*, 1986).

EMISSIONS IN THE SELECTED IIASA REGIONS

There will clearly be regional variation in the development of SO_2 and NO_x emissions. Emissions are strongly related to the more or less prudent allocation of fossil fuels and to changes in consumption of fossil fuels over time in a specific region. To illustrate the situation, we select IIASA Regions I, II, and all of III for detailed examination. We consider use of fossil fuels for the years 1975 and 2030 (Fig. 8) and the emissions of SO_2 and NO_x to which they lead (Fig. 9). A distinction is made between employing fossil fuels without degradation of quality (case 1) and with degradation (case 2) for the year 2030.

The range of results is striking. For example, a decrease of more than 30% in the emission of SO_2 for case 1 in Regions I and II and nearly constant emissions in Region II can be realized, while the consumption of the fossil fuels is increasing. However, if a quality degradation is assumed for 2030, there is a sharp increase in SO_2 emissions in Region II and nearly constant figures in Regions I and III. For Europe, which covers Region II and a great part of Region III, it is probable that neither level of emissions would be environmentally acceptable to sustain between now and 2030 and beyond. But, we should keep in mind that no abatement measures are considered. Therefore, these results may be interpreted to underline the necessity for such measures.

If one considers the specific amounts of SO_2 or NO_x emitted per TWyr of fossil fuel consumed, one gets an idea of the effects of allocation changes and the quality degradation of fossil fuels (Table 6). In both cases, ratios of SO_2 and NO_x emissions decrease in Regions I and III, but in Region II the SO_2 emission ratio shows a sharp decrease in case 1 and a sharp increase in case 2.

A comparison of the allocation of fossil fuels in 1975 and 2030 explains these results (Fig. 8). In Region I, the significant increase in coal consumption is due primarily to gasification. This leads to fewer emissions as the coal would have been used for electricity generation. The synthetic liquids produced by the gasification are used in all sectors; therefore, oil consumption is sharply reduced. Both effects

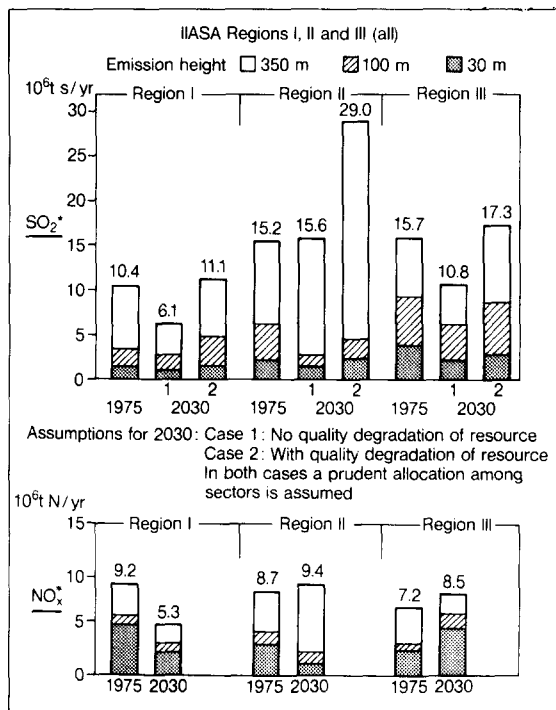


Fig. 9. Calculated amounts of SO_2 and NO_x emitted in 1975 and 2030 according to three different emission heights for selected IIASA-regions (for definition see Fig. 5). *See footnote in Table 3.

Table 6. Ratio of the amounts of SO₂ and NO_x emitted to the amounts of fossil fuels consumed in 1975 and 2030 for selected IIASA-regions (for definition see Fig. 5). Case 1: quality of fossil fuels assumed constant with time. Case 2: quality of fossil fuels assumed to deteriorate with time.

		Region I	Region II	Region III
SO ₂ *	1975	4.7	9.0	8.7
	2030 case 1	2.6	6.2	4.3
	case 2	4.7	11.6	6.9
10 ⁶ t S/TWyr				
NO _x *	1975	4.2	5.2	4.0
	2030	2.2	3.7	3.4
10 ⁶ t N/TWyr				

*See footnote in Table 3.

result in a reduction of SO₂ emissions. The reduction in oil consumption reduces NO_x emissions significantly (Fig. 9).

In Region II, the largest share of coal consumption is for electricity generation. Therefore, emissions are high, especially in case 2. Simultaneously, the consumption of gas is increasing. The change in allocation changes the share of emissions related to the emission heights. This is an important fact for the dispersion calculations.

In Region III, the increased consumption of coal is going into gasification, and the consumption of gas has doubled and is used in the industry and household sectors. Oil consumption is nearly the same in 2030 as in 1975, although transportation's share of that consumption has doubled. This means that the distribution to the emission heights for SO₂ is nearly the same, but concerning NO_x there is a doubling for 30 m and a reduction for 350 m.

Clearly it is possible that in spite of increasing consumption of fossil fuels, the emissions of SO₂ and NO_x can be reduced through prudent allocation of fossil fuels even without consideration of abatement measures. Each sectoral allocation of fossil fuels leads to emissions in specific heights and this results in a related deposition situation.

THE SITUATION IN EUROPE

It is informative to consider first the historical evolution of the use of coal and oil and the related emissions of SO₂ in Europe (Fig. 10). Until the year 1950, the evolution of the use of fossil fuels and the associated emissions of SO₂ were largely determined by coal. With the sharp increase in the consumption of oil from the 1950s until the present day, we have had a second distinct phase of SO₂ emissions. For the year 2030, the strong difference in the SO₂ emissions between case 1 and case 2 shows the potential importance of the quality of fossil fuels. The value of detailed information about the quality of fossil fuel resources is thus clear.

Table 7 illustrates the different evolution of the absolute and energy specific values of SO₂ emissions. There is a decrease in sulphur emissions in relation to

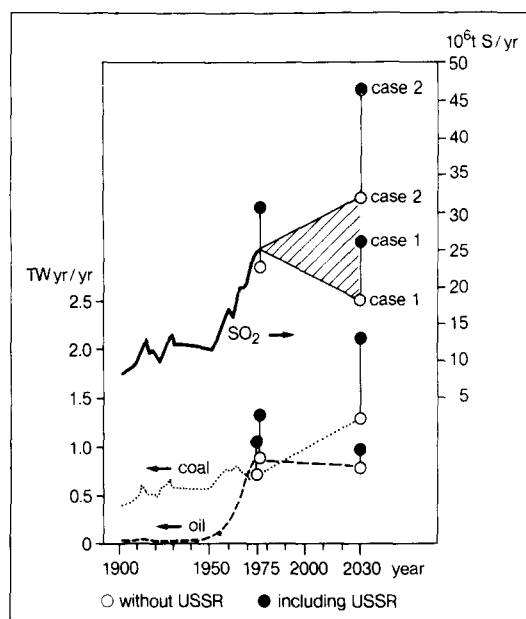


Fig. 10. Historical evolution of the use of coal and oil (amounts in terawatt-year per year, TWyr/yr) and related emissions of SO₂* in Europe between 1900 and 1972 (Swedish University of Agricultural Science, 1984) and for the year 1975 and 2030 determined in this study. For definition of cases 1 and 2 see Table 6. *See footnote in Table 3.

energy production because of technological evolution and, at the same time, an increase in the absolute value because of the large increase in the consumption of oil. In 2030, prudent allocation of fuels could again partly offset increases in emissions resulting from an additional increase in energy consumption. But if a degradation in the quality of fuels is assumed, SO₂ emissions in Europe in our scenario will grow to more than 30 million tons of sulphur, or more than 47 million tons if one includes the Soviet Union. Therefore, the problem of SO₂ emissions in Europe looms large.

Figure 11 shows the total deposition of sulphur compounds in mgS/m²/yr for the year 1975. Total deposition is the sum of dry and wet deposition, calculated using the statistical meteorological model.

Table 7. Evolution of the amounts of SO₂ emitted in absolute and in energy specific terms (ratio of emission to consumption of fossil fuels) from 1900 to 2030 in Europe. For definition of cases 1 and 2 see Table 6.

	Emissions of SO ₂ *	
	in absolute terms 10 ⁶ t S/yr	in energy specific terms 10 ⁶ t S/TWyr
1900	9	22.5
1950	11	18.3
1975	25	14.7
2030 case 1	16	9.0
case 2	32	16.0

*See footnote in Table 3.

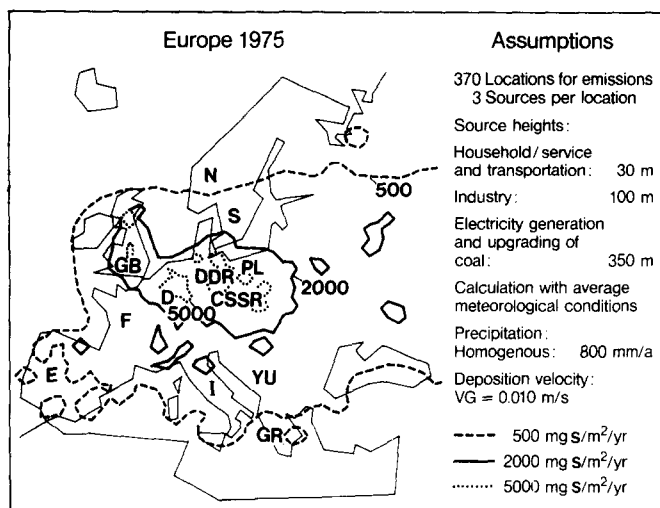


Fig. 11. Isocontours of the calculated amounts of sulphur compounds* deposited for Europe in 1975. *See footnote in Table 3.

The results are presented as isocontours of total deposition for 500, 2000, and 5000 mgS/m²/yr. Figure 11 lists the main assumptions for the calculations. These assumptions have been varied in sensitive analyses and will be reported in a subsequent publication (Häfele *et al.*, 1986).

In 1975 total deposition of sulphur compounds appears to have exceeded 500 mgS/m²/yr throughout Europe except in northern regions of Norway and Sweden. The Swedish Ministry of Agriculture (1982) asked for a maximum deposition of sulphur in susceptible regions of 300–500 mgS/m²/yr, although the environmental consequences of any particular deposition rate are largely unknown. There is a great need for standards by which to judge the effects of SO₂ deposition. Nobody knows what it means effectively when deposition rates in Central Europe are four

times the proposed Swedish limit. In parts of Belgium, Great Britain, East and West Germany, and Czechoslovakia, the above mentioned Swedish limit is exceeded by a factor of more than ten. The Soviet Union for 1975 is estimated to have had about $9 \cdot 10^6$ tS of SO₂ deposition assumed to be spread over a wide area—the effect of tall stacks constructed for coal-fired power plants.

Similar deposition calculations are presented for 2030 (Fig. 12). Because of the lack of benchmarks for absolute terms, it is useful to use relative terms. Thus, the patterns for the year 2030 are compared with those for 1975 to accentuate the geographical changes of the values.

We have pointed out that, if one assumes no degradation in the quality of fossil fuels, emissions decrease in Region III and remain nearly constant in

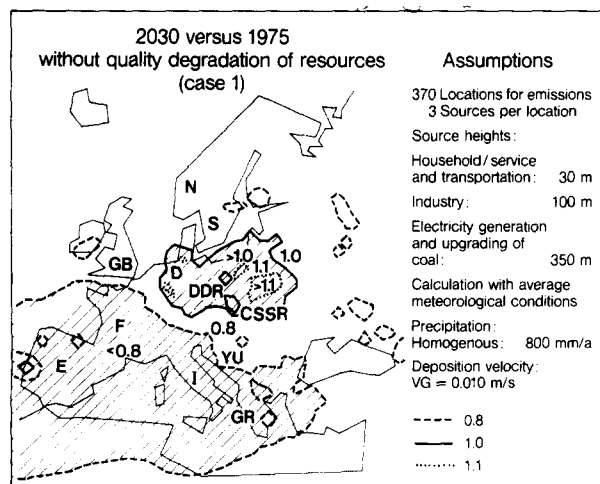


Fig. 12. Isocontours for the relative changes (2030 vs 1975) of the amounts of sulphur compounds deposited in Europe calculated for case 1.

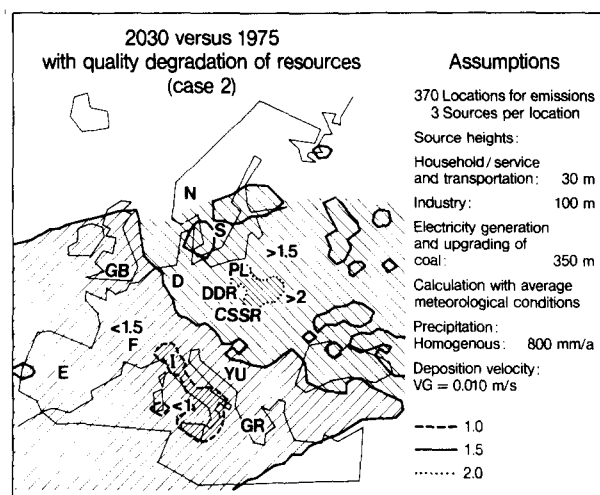


Fig. 13. Isocontours for the relative changes (2030 vs 1975) of the amounts of sulphur compounds deposited in Europe calculated for case 2.

Region II. This results in a cumulative decrease in the emissions in Europe. With regard to deposition, the same holds true for the northern and western parts of Europe, while the East, specifically the Soviet Union remains unchanged. But the deposition values increase for Middle Europe (Fig. 12). Here the largest changes—more than 10%—take place in Czechoslovakia, the German Democratic Republic, and Poland. Thus, although the emission situation improves for Europe as a whole, the problem of sulphur deposition in Middle Europe becomes worse.

If a quality degradation of resources is assumed, it can be expected that both emissions and depositions will become much worse in Europe, except in Italy (Fig. 13). Europe is then divided into an eastern part with more than a 50% increase in emissions and a western part with less than a 50% increase. The most affected area will be—as in the previous case—Czechoslovakia, the German Democratic Republic, and Poland. Rates of emissions and deposition in 2030 could more than double those in 1975.

To sum up, the change in the sectoral allocation of fossil fuels leads to a shifting of deposition to the East, so that by the year 2030 there would be a concentrated area, specifically in Middle Europe, with a very high rate of SO_2 deposition. A degradation in the quality of the resources will not change the pattern of the deposition structure, but will lead to higher levels of deposition.

The analogous situation for deposition of nitrogen compounds in 1975 is presented in Fig. 14, with isocontours of total deposition of 200, 1000, and 5000 $\text{mgN/m}^2/\text{yr}$. There is an even greater lack of knowledge, and consequently a greater problem of standards, for nitrogen than for sulphur, because the interactions with other chemical species and effects are more complex.

Because of the dense vehicle traffic, there is a more western concentration in Europe for nitrogen deposi-

tion. Deposition exceeds 1000 $\text{mgN/m}^2/\text{yr}$ for Great Britain and Middle Europe. While this is more than a tenth of the natural deposition of nitrogen in these latitudes (Bauer, 1982), the environmental consequences cannot be fully described or traced. In areas of the Federal Republic of Germany, the Netherlands, and France, the deposition level is calculated to be 5000 $\text{mgN/m}^2/\text{yr}$ or more.

In our scenario, nitrogen deposition in 2030 will become as much as 50% greater than in 1975 in those regions that are already most affected (Fig. 15). The problem intensifies to the west and to the north. This can be explained by the increasing share of oil consumption in Region III, primarily as fuel for motor vehicles. Nitrogen deposition in Eastern Europe will remain as it was in 1975. Because most of the emissions of nitrogen compounds are at a height of 30 m, the problem is especially a local one. This is in contrast to sulphur emissions, which in Eastern Europe occur mainly at a height of 350 m.

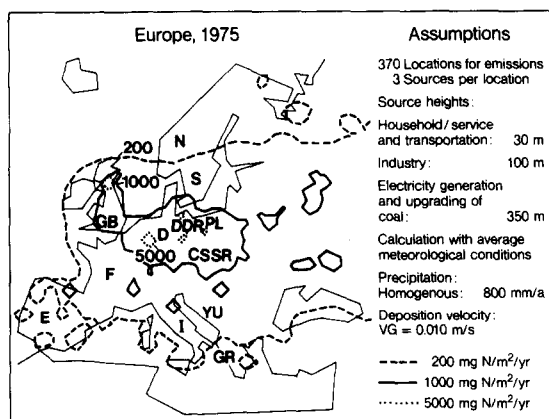


Fig. 14. Isocontours of the calculated amounts of nitrogen compounds* deposited for Europe in 1975. *See footnote in Table 3.

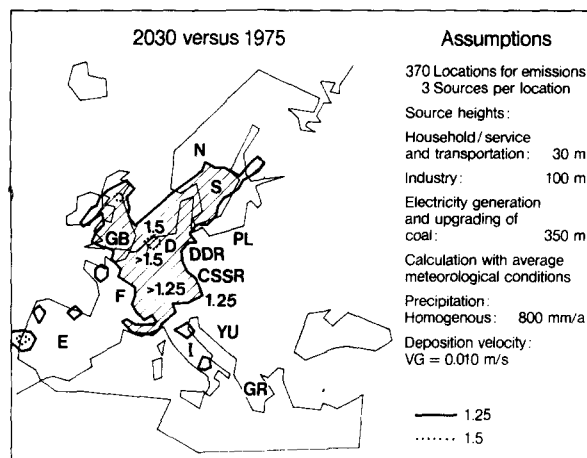


Fig. 15. Isocontours for the relative changes (2030 vs 1975) of the amounts of nitrogen compounds deposited in Europe.

The aim of this paper is not to say that these particular levels of emissions and depositions will occur, but rather help identify the structure of the issues, their sensitivities, and the need for further investigation. Nevertheless, we can be relatively confident that Middle and Eastern Europe will remain critical cases that require continent-wide action. Results we report elsewhere (Häfele *et al.*, 1986) indicate that for portions of China and other geographical regions, there can be similar situations.

A TECHNICAL OPTION TO REDUCE EMISSIONS

While continuation of present trends would be worrisome, we wish equally to emphasize that there

are attractive possibilities for industrial systems that would reduce pollution significantly. Indeed, one such possibility would be an energy system with essentially zero emissions. During the past two years, a working group in the KFA-Jülich has conducted extensive systems analyses to study the technical and economic feasibility of such a system (Häfele *et al.*, 1985). The system appears technically feasible and economically competitive but would require large institutional changes. Since institutions generally evolve slowly, one cannot expect widespread installation and operation of a zero emissions energy systems soon. Nevertheless, we offer the following description of a novel horizontally integrated energy system (Fig. 16) as an example of how emissions could be drastically reduced.

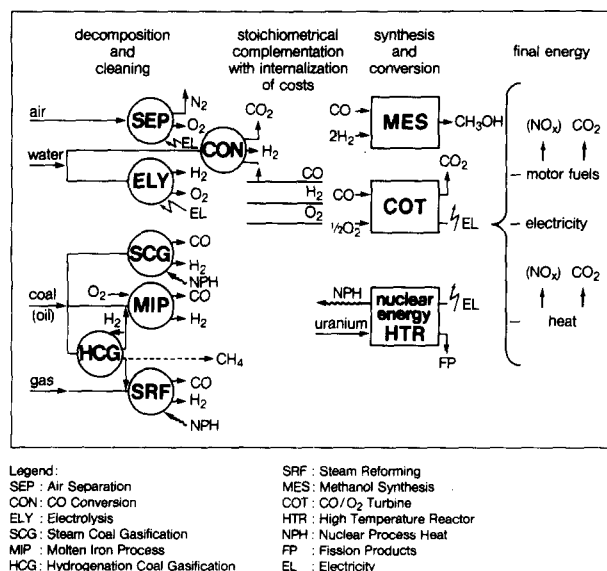


Fig. 16. Scheme for the novel, horizontally integrated, zero emission energy system according to Häfele *et al.* (1985).

Table 8. Amounts of SO_2^* emitted in 1975 and 2030 for the IIASA world regions (for definition see Figure 5), for the developed regions (I + II + III) and for the less developed regions (IV + V + VII) in 10^6 tS/yr . For definition of cases 1 and 2 see Table 6.

Region	1975	2030	
		case 1	case 2
I	10.4	6.1	11.1
II	15.2	15.6	29.0
III (all)	15.7	10.8	17.3
IV	2.9	10.2	14.2
V	5.3	16.8	20.9
VII	5.5	11.4	22.6
I+II+III	41.3	32.5	57.4
IV+V+VII	13.7	38.6	57.7
World	55.0	70.9	115.1

*See footnote in Table 3.

A fundamental element of the system is to have a set of inputs to the combustion process: air, water, coal, oil (including low-grade oil, tar sands, shale oil), and gas. The set of inputs to the system first becomes disintegrated, or decomposed. For instance, coal can be decomposed in a molten iron bath with inputs of oxygen and electricity. The principal product is synthetic gas, a mixture of carbon monoxide and hydrogen. All ashes, including practically all the sulphur, form a slag on the surface of the iron bath that can easily be removed. Steam coal gasification with the application of nuclear power from a high-temperature reactor also results in the desired carbon monoxide and hydrogen. Alternatively, the two gases can be produced by decomposition of natural gas with the shift reaction or by applying external process heat from a nuclear power station. The key feature is the range of options for sources of hydrogen and other intermediate energy forms.

The decomposition procedure can also be used to separate nitrogen from the air that support combustion, and the nitrogen in the air is thus eliminated as a source of NO_x . NO_x would then come only from the nitrogen content of coal and could also be separated in the molten iron bath, for example. In other words, air is no longer used as a combustion partner.

Water is decomposed either electrolytically or in a thermochemical conversion process using carbon monoxide. The objective is to achieve a stoichiometrical balance for the three lines: carbon monoxide, hydrogen, and oxygen. The idea is then to integrate horizontally with various routes to make use of these intermediate fuels only as stoichiometry requires them.

For the case where CO_2 is desired for combustion, one would only take the amount of CO and O_2 required to produce the CO_2 . In this connection high temperature turbines that yield thermal efficiencies of up to 60% can be applied, as investigated by a group under T. H. Lee at the Massachusetts Institute of

Technology. Another possibility is the emission-free composition of liquid hydrocarbons, such as methanol, as the KFA-Jülich is investigating on a pilot scale. The idea again is to have only the stoichiometrical allocation of the clean intermediate energy forms for the desired synthesis.

Energy use would still result in emissions, but they would be free of SO_2 , and the NO_x share would be drastically reduced. And by eliminating the flow of environmentally hazardous mass streams at the front end of the fuel cycle, the heavy metal content of the fuels is contained as well.

A GLOBAL VIEW OF THE EMISSIONS OF SULPHUR AND NITROGEN

In this section we describe the emissions of sulphur and nitrogen on a global scale by looking briefly at the situation for all of the IIASA regions. While these estimates are individually subject to great uncertainties, the calculations probably do give a reliable overall sense of the order of magnitude and direction of global changes.

In the case of sulphur, we calculate there were about $50 \cdot 10^6 \text{ tS}$ of anthropogenic SO_2 emissions in 1975: 75% coming from the developed regions, 25% from the less developed regions (Table 8). If we follow the IIASA low-scenario for the year 2030, we find that because of a prudent allocation of fossil fuels in the developed regions and the large increase of fossil fuel consumption in the less developed regions, the most severe emissions problems shift significantly to the less developed regions. Globally, SO_2 emissions increase, even doubling in the case that assumes degradation in fuel quality.

For NO_x emissions we give a more geographical presentation (Fig. 17) and compare natural and

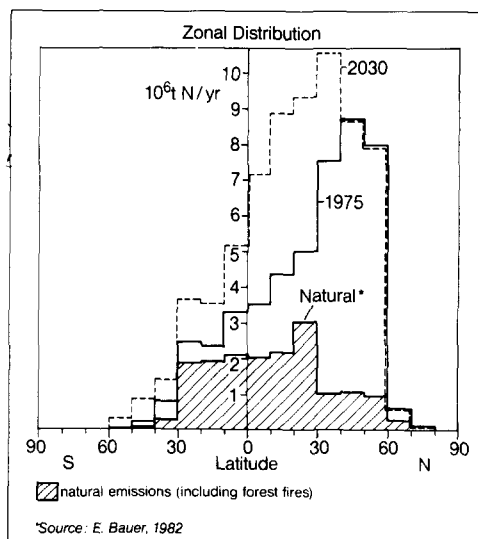


Fig. 17. Distribution according to latitude of the natural (Bauer, 1982) and the anthropogenic emissions calculated in this study of nitrogen for 1975 and 2030.

anthropogenic emissions. This is not possible for sulphur because the range of estimates of natural fluxes in the literature is very wide. The countries of the IIASA Regions I, II, and III are situated predominantly between 30 and 60° north. At present, the peaks of anthropogenic emissions of NO_x occur in this range, exceeding the natural emissions by a factor of 6–7. South of the equator, the natural emissions, including the ones from forest fires, exceed the anthropogenic ones.

In 2030 the anthropogenic emissions are estimated to shift toward the equator. Nearly all the inhabited latitudes of the northern hemisphere will have values comparable to or above peak values of 1975, and the natural emissions will be exceeded by a factor of 4–5 over the entire range. Given the complexity of the global nitrogen cycle, one must take great care in projecting changes, but it is clearly an urgent task to elaborate what it means when the natural cycle of nitrogen is disturbed by anthropogenic emissions on this scale.

CONCLUSIONS

Emissions and depositions of sulphur and nitrogen related to energy systems are of continent-wide, even global significance. Amounts and geographical structure depend critically on the following:

- allocation of primary energy to end users
- allocation of fossil fuels to energy users
- quality of fossil fuels
- technology in use
- emissions heights
- use of abatement measures

In Europe SO₂ depositions tend to occur in the center and east and NO_x depositions in the center and west. Although there could be a lower level of emissions in 2030 than in 1975, deposition could equally as readily increase and nearly double in some regions. Middle and Eastern Europe seem to be a potential worst case. In other regions, specifically China, Latin America, and Asia, there is also a strong potential for increase in both SO₂ and NO_x emissions. This could lead to serious deposition problems in, for example, China, Korea, Japan, and India.

The process of identifying and clarifying the problem reveals weak links in our knowledge. There is a serious lack of data on quality of fuel resources, including content of sulphur and nitrogen and other critical characteristics. There is a lack of knowledge about the chemistry of the atmosphere and the transport of aerosols, which determine relations between emissions and depositions. There is an absence of quantitative figures for rates of decomposition and cumulative processes in the environment. While natural emissions and deposition may be exceeded by anthropogenic ones many times over, it is not known whether there are sound natural benchmarks for concern control. For many purposes, we lack stan-

dards by which to evaluate deposition of NO_x and SO₂. Moreover, emissions of SO₂ and NO_x are symptomatic of systems of energy and industrial production which also intrinsically generate great concern about such issues as environmental releases of heavy metal and greenhouse gases.

However, we also observe that powerful technical means exist to improve the outlook for fossil fuel use. Effective programs of scientific research and technological development and concerted action at many levels are required to clarify the complex problem of environmentally harmonious global development and broaden the range of constructive strategies.

Acknowledgements—We would like to express our gratitude to Prof. Kley, Institute of Chemistry 2 of the Nuclear Research Center in Jülich, for his support concerning the atmospheric cycles of sulphur and nitrogen. Furthermore, we would like to thank Dr P. Müller and Dr H. J. Schenk, Institute of Chemistry 5 of the Nuclear Research Center in Jülich, and also Bergbauforschung in Essen, who supported us in the collection of data for the quality of fossil fuels.

REFERENCES

- Allhorn H. *et al.* (1984) *Kohleverwendung und Umweltschutz*. Springer, Berlin.
- Balabanov T. *et al.* (1982) *The IIASA Set of Energy Models*. Documentation of the global runs. IIASA, Laxenburg.
- Bauer E. (1982) *Natural and anthropogenic sources of oxides of nitrogen (NO_x) for the troposphere*. Institute for Defense Analyses. Paper P-1616.
- Bolin B. and Cook R. B. (Ed.) (1983) The major biogeochemical cycles and their interactions. *SCOPE 21*. Wiley, Chichester.
- Brauer H. (1984) Reinhaltung der Luft in großen Städten. *Staub-Reinhaltung Luft* **44**, 85–94.
- Brenk H. D. and Vogt K. J. (1981) The calculation of wet deposition from radioactive plumes. *Nuclear Safety* **22**(3), 362–371.
- Chamberlain A. C. (1953) Aspects of travel and deposition of aerosol and vapor clouds. *AERE HP/P* 1261.
- Chamberlain A. C. and Chadwick R. C. (1953) Deposition of Airborne Radioiodine Vapor. *Nucleonics* **11**, 8–22.
- Chant V. G. (1981) Two global scenarios. The evolution of energy use and the economy to 2030. *IIASA RR-81-14*. Laxenburg.
- Committee on the Atmosphere and the Biosphere (1981) *Atmosphere-Biosphere Interactions: Towards a Better Understanding of the Ecological Consequences of Fossil Fuel Combustion*. National Research Council, Washington.
- Der Bundesminister des Inneren (1977) *Allgemeine Berechnungsgrundlage der Strahlenexposition durch Emission radioaktiver Stoffe mit der Abluft*. Empfehlung der Strahlenschutz-kommission, Bonn.
- Deutsche Shell Aktiengesellschaft (1982) Stabilisierung nach der Trendwende. Szenarien für den Energiemarkt der Bundesrepublik Deutschland bis zum Jahr 2000. *Aktuelle Wirtschaftsanalysen Nr. 14*. Hamburg.
- Dickinson R. E. and Cicerone R. J. (1986) Future global warming from atmospheric trace gases. *Nature* **319**, 109–115.
- Garnreiter F. (1983) *Auswirkungen verstärkter Maßnahmen zum rationellen Energieeinsatz auf Umwelt, Beschäftigung und Einkommen*. E. Schmidt, Berlin.
- Geschwandtner G. *et al.* (1985) Historic emissions of sulphur and nitrogen oxides in the United States from 1900 to 1980. *United States Environmental Protection Agency EPA-600/7-85009a*. Washington.

- Häfele W. (Ed.) (1981) *Energy in a Finite World. A Global Systems Analysis*. Ballinger, Cambridge, Massachusetts.
- Häfele W. et al. (1985) Das Konzept der neuartigen, horizontal integrierten Energiesysteme. *Technische Rundschau* 18/85, 17–25.
- Häfele W. et al. (1986) *Future use of Fossil Fuels. A Global View on Related Emissions and Depositions*. KFA-report, Jülich.
- Hordijk L. (1985) Private communication. *International Institute of Applied Systems Analysis*. IIASA, Vienna.
- Ivanov M. V. and Freney J. R. (Ed.) (1983) The global biogeochemical sulphur cycle. *SCOPE 19*. Wiley, Chichester.
- Khan A. M. and Holz A. (1982) Evolution of future energy demands till 2030 in different world regions: an assessment made for the two IIASA scenarios. *IIASA RR-82, 14* Laxenburg.
- Kley D. (1985) Private communication. Nuclear Research Center of Juelich.
- Lahmann E. (1984) Luftqualität in Ballungsgebieten. *Staub-Reinhalung Luft* 44, 134–137.
- Lehmhaus J. et al. (1985) *Deposition Patterns and Transport Sector Analysis for a Four Year Period*. The Norwegian Meteorological Institute, Oslo.
- Lichtblau J. H. (1983) Oil's role in the energy future. In *Preprint 11th World Petroleum Congress, RTD 9*. Mineral Research Institute of New York.
- Ministry of Agriculture (1982) *Acidification Today and Tomorrow. A Swedish Study Prepared for the 1982 Stockholm Conference on the Acidification of the Environment*, Stockholm.
- National Research Council (1983) *Changing climate. Report of the Carbon Dioxide Assessment Committee*. National Academy Press, Washington.
- Pasquill F. (1974) *Atmospheric Diffusion*. Van Nostrand, London.
- Ramanathan V., Cicerone R. J., Singh H. B. and Kiehl J. T. (1985) Trace gas trends and their potential role in climate change. *J. Geophys. Res.* 90, No. D3, 5547–5566.
- Report on the Environment by the Technology Growth and Employment Working Group Presented to the Prime Minister by Command of Her Majesty (1985)*. London.
- Statistical Office of the European Community (1976) *Quarterly Bulletin of Energy Statistics*. EUROSTAT 4-1976.
- Söderlund R. and Svensson B. H. (Eds) (1976) The global nitrogen cycle. In *Nitrogen, Phosphorus and Sulphur—Global Cycles*. SCOPE 7, Ecological Bulletins, Swedish Natural Science Research Council.
- Stockwell W. R. and Calvert J. G. (1983) The mechanism of the HO-SO₂ reaction. *Atmospheric Environment* 17, No. 11, 2231–2235.
- Swedish University of Agricultural Science (1984) *Effects of Air Pollution on Forest Land—Outline for a Research Programme*. Stockholm.
- United Nations (1981) *1979—Yearbook of World Energy Statistics*. Department of International Economic and Social Affairs. *12th World Energy Conference (1983)*, New Delhi.