Scenarios of Global Anthropogenic Emissions of Air Pollutants and Methane Until 2030

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Abstract

We have used a global version of the Regional Air Pollution Information and Simulation (RAINS) model to estimate anthropogenic emissions of the air pollution precursors sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), primary carbonaceous particles of black carbon (BC), organic carbon (OC), and methane (CH_4). We developed two scenarios to constrain the possible range of future emissions. As a baseline, we investigated the future emission levels that would result from the implementation of the already adopted emission control legislation in each country, based on the current national expectations of economic development. Alternatively, we explored the lowest emission levels that could be achieved with the most advanced emission control technologies that are on the market today. This paper describes data sources and our assumptions on activity data, emission factors and the penetration of pollution control measures. We estimate that, with current expectations on future economic development and with the present air quality legislation, global anthropogenic emissions of SO_2 and NO_x would slightly decrease between 2000 and 2030. For carbonaceous particles and CO, reductions between 20% and 35 % are computed, while for CH_4 an increase of about 50% is calculated. Full application of currently available emission control technologies, however, could achieve substantially lower emissions levels, with decreases up to 30 % for CH_4, 40% for CO and BC and nearly 80 % for SO_2.

Key word index: air pollution, climate change, anthropogenic emissions, global analysis

1. Introduction

While there are extensive discussions in the scientific literature about the possible future range of global greenhouse gas emissions (e.g., Nakicenovic *et al.*, 2000, IPCC, 2007), we find a comparably modest understanding of how global emissions of the conventional air pollutants are likely to develop in the coming decades. Such information is not only relevant for designing (cost-)effective mitigation strategies that provide acceptable levels of air quality to the population in industrialized and developing countries, but it is also essential input to modelling studies that assess the future chemical composition of the earth's atmosphere (e.g., Dentener *et al.*, 2006, Unger *et al.*, 2006) and their impacts, e.g., on human health (West *et al.*, 2006). Such studies provide increasing evidence about the relevance of hemispheric scale transport of air pollutants, through which the evolution of air pollutant emissions at the global scale becomes of direct interest for air quality managers dealing with the regional and local scales (Akimoto, 2003; Dentener *et al.*, 2005).

This paper explores the possible range in which global emissions of sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), primary carbonaceous particles of black carbon (BC), organic carbon (OC) and methane (CH_4) could develop by 2030. We generated two scenarios to constrain the possible span of future emissions. As a baseline, we investigate emission levels that would result from the implementation of the already decided emission control legislation in each country, based on the current national expectations of economic development. Alternatively, we estimate the lowest emission levels that could be achieved, for the same assumptions on economic development, with the most advanced emission control technologies that are on the market today.

For this analysis we used a global version of the Regional Air Pollution Information and Simulation (RAINS) model (Amann *et al.*, 2001) and its GAINS extension to greenhouse gases (Höglund-Isaksson and Mechler, 2005). The global model comprises implementations for all countries in Europe (Amann *et al.*, 2006; Kupiainen and Klimont, 2004) and Asia (Cofala *et al.*, 2004; Klimont *et al.*, 2001), which are complemented with country-specific data for North America, Russia and Australia. Latin America, Africa and the Middle East are represented as aggregated world regions only. Thereby, we prepared estimates of the anthropogenic emissions for the period 1990 to 2030 for 75 countries or country groups[1]. Our analysis does not include emissions from international shipping and from aviation. Emissions from open biomass burning (deforestation, savanna burning, vegetation fires) and natural emissions are also excluded.

2. Projections of activity levels

For all countries and regions included in this analysis, we collected the available current national perspectives on the sectoral economic and energy development up to the year 2030. For regions where we did not find national projections, we used results from regional modelling studies. We compiled data on production levels for the main industrial sectors, on fuel consumption by economic sector and fuel type, and different classes of transport activities. We collected

[1] Detailed emissions by scenario, country and sector are available from http://www.iiasa.ac.at/rains/Glob_emiss/global_emiss.html

projections of livestock numbers, crop farming and waste treatment and disposal.

The national projections of future activities that we have collected for our study reflect expectations of national governments and thereby, in many cases, probably merely policy ambitions rather than the most likely developments. There is no guarantee of international consistency, e.g., between the volumes of exports and imports or in the underlying assumptions on the development of oil prices. Nonetheless, the value of this set of bottom-up projections is that it reflects the expectations on economic development in the coming decades as seen today by countries.

For the Member States of the European Union, for Norway, Switzerland and for Turkey we have based our analysis on the activity projections that have been employed by the European Commission for the EU Thematic Strategy on Air Pollution (CEC, 2005). For other European countries and for Russia we used the national projections that have been submitted to the Convention on Long-range Transboundary Air Pollution (Cofala *et al.*, 2006). Activity projections for the United States (US), Canada, and Australia have been extracted from national reports (EIA, 2005; NRCan, 2000; DPMC, 2004). For Asia we have taken the national projections collected for the RAINS-Asia implementation (Cofala *et al.*, 2004). For the other world regions we have applied the trends of future economic and energy developments of the IPCC SRES B2 MESSAGE scenario (Riahi and Roehl, 2000; Nakicenovic *et al.*, 2000) to the activity levels reported in international statistics for the year 2000 (IEA, 2002; UN, 2003). Since the official energy statistics of many developing countries do not include total biomass fuel consumption, biomass use data for Latin America and Africa were taken from Riahi and Roehl, 2000.

Table 1 summarizes assumptions of our national scenario on future population, gross domestic product (GDP) and primary energy consumption. Compared with the year 1990, world population is expected to increase by 60% until 2030, with highest growth rates in Africa and Latin America (120%), while population in Central and Eastern Europe and in the former Soviet Union is expected to stabilize at the 1990 levels. Worldwide per-capita income (in market exchange rates) is expected to more than double by 2030, with income levels in Asia growing by a factor of eight. As a consequence, global GDP would increase by a factor of 3.6, and by a factor of 13 in Asia. While the assumptions on population growth in the SRES A2 and B2 scenarios are similar to the national perspectives, the national projections foresee higher economic growth than the two SRES scenarios.

For the 260% increase in GDP, the national perspectives envisage 80% higher energy consumption, which implies a decrease in the energy intensity of GDP by almost 50% up to 2030. The SRES scenarios are less optimistic about energy intensity improvements. The B2 scenario assumes for 2030 five percent higher energy consumption, but 13 percent less GDP than the national projecitons, resulting in a 40% decrease in energy intensity. In the A2 scenario, which features slow economic development, only a 12% decrease in energy intensity occurs.

The structural composition of energy consumption is another critical factor for air pollutant emissions (Figure 1). National projections reflecting the current energy policies envisage globally a 70% increase of coal use, most of it in Asia. Different policy assumptions lead in the

SRES B2 scenario to only a 10% growth in coal use, while in the A2 scenario coal demand increases till 2030 by 80%. All scenarios agree on a stronger reliance on natural gas (+120% to +140%). Future perspectives on nuclear power range from a 60% capacity expansion in the national projections to an increase by a factor of three in the SRES scenarios.

To feed the 60% increase in world population, available projections of agricultural activities foresee approximately 30% higher livestock numbers in 2030 and a 15% expansion in rice cultivation area.

3. Emission factors

For our analysis we applied emission factors that reflect country-specific conditions (e.g., in fuel quality, combustion technologies, fleet composition, maintenance levels, etc.) as well as the effects of applied emission control technologies. For NO_x, we extracted such emission factors from the available RAINS databases for Europe and Asia (Cofala and Syri, 1998b), which have been extensively reviewed by European and Asian experts from academia, governments and industry. For other countries default factors that distinguish the effects of applied emission control measures have been used. Emission factors for CO are based on the IPCC guidelines (Houghton *et al.*, 1997) and modified for country-specific conditions (e.g., for wood burning in the domestic sector and for mobile sources) to the extent we had appropriate knowledge available. For SO_2, information has been taken from the RAINS databases (Cofala and Syri, 1998a) and modified for other countries with coal quality parameters provided in the IEA Coal Research database (IEA, 1997). Our estimates of black carbon (BC) and organic carbon (OC) emissions follow the RAINS methodology for particle emissions (Klimont *et al.*, 2002), which has been modified to capture regional and country-specific characteristics of BC and OC emissions (Kupiainen and Klimont, 2007) and extended to developing regions with data from Bond *et al.*, 2004. For CH_4, we have developed country-specific emission factors (Höglund-Isaksson and Mechler, 2005) based on the international literature (Houghton *et al.*, 1997; US-EPA, 2005; UNFCCC, 2006).

We reflect the future evolution of emission factors by considering the country-, sector- and technology-specific effects of the application of emission control measures imposed by current legislation in each country. The RAINS model contains reviewed databases on the technical features of the most important emission control technologies. For this study we compiled the state of national legislation on emission controls as of the end of 2004 and its evolution in the coming years as laid down in the present national legislations. For Europe and North America, we consider the current national and international fuel quality and source-specific emission standards. The rapid progress in the introduction of stringent emission control standards for vehicles in Asia and Latin America is summarized in e.g., ADB, 2005 and DieselNet, 2005. For stationary sources, we relied for South-East Asia on country-specific information that was collected in the context of the RAINS-Asia II project (IIASA, 2001; Cofala *et al.*, 2004), and for other countries on the emission standards handbook (McConville, 1997).

To constrain the future range of emissions, we also estimated the theoretical scope for emission controls offered by full application of all presently available technical emission control measures. With the emphasis on a theoretical analysis of the long-term potential, we disregarded practical limitations on the penetration of new emission control measures that result from the gradual turnover of existing capital stock (except for the residential sector). We also did not estimate the obviously high costs of such action. On the other hand, we did not consider in this scenario the additional potential for emission reductions offered by structural changes (e.g., increased energy efficiency measures, fuel substitution, more efficient production technologies or reduced transport demand). Earlier studies have shown that such measures offer considerable potential for further reductions, partly even at low costs (e.g., Van Vuuren *et al.*, 2006).

4. Emission scenarios

4.1 Past emissions

We calculated national and sectoral emissions for past years (1990 – 2000) and for the projection period up to 2030 (Table 4 to Table 9, Figure 2). For 1990, we estimate global emissions of SO_2 at about 120 Tg. As a result of the strict controls that have been implemented in OECD countries and the economic restructuring in Central and Eastern Europe after 1990, we find a 20% decline in SO_2 emissions for the year 2000. Largest contributions to global anthropogenic emissions come from the power sector (more than 50%) and industry (about 1/3).

In contrast to SO_2, we see only a slight decrease in global NO_x emissions (84 Tg in 1990) between 1990 and 2000. Reductions in the OECD countries and Central and Eastern Europe were largely compensated by higher emissions in developing countries. Road transport constituted the most important source of anthropogenic NO_x emissions (41% in 2000), followed by power plants, industry and non-road vehicles (21%, 16% and 13%, respectively).

For CO emissions (523 million tons in 1990), we obtain a 4% percent decline in the following decade. About half of anthropogenic CO emissions originated from the residential/commercial (domestic) sector and one third from road transport. Industry and non-road vehicles contributed 8% and 6% respectively.

For BC, we calculate total global emissions in 1990 and 2000 at 5.5 and 5.3 Tg C, respectively, with more than 60% released in Asia. Approximately 65% of anthropogenic emissions originate from small-scale combustion sources (heating and traditional cooking stoves burning solid fuels, mainly biomass). Transport activities contributed another 20-25% to total emissions. However, these shares show large variations across the world. For instance, in the OECD countries the residential sector emitted about 25% of total emissions, in Central and Eastern Europe some 50%, in Asia 60-80% and in Africa more than 80%. Conversely, more than 70% of European BC emissions originate from the transport sector, but less than 10% in Africa.

Global emissions of OC (about 12 Tg C) exhibit a similar temporal trend to BC, with about 80% originating from small-scale domestic combustion sources (primarily biomass use in stoves) and 10% from transport activities. Regional differences in the contribution from transport are even more pronounced than for BC. While in the developing world only a few percent originate from this sector, the shares in OECD countries range from 30% in Western Europe to about 60% in Australia and North America.

We estimate for 1990 263 Tg CH_4 emissions from anthropogenic sources, and a 10% increase by the year 2000. About one third is caused by livestock farming, 30% from the energy sector and 23% from waste treatment and disposal.

We compared our estimates for past years with other national and international emission inventories. For SO_2 and NO_x, our assessments for most of the industrialized countries in Europe and North America do not differ by more than 10% from the national inventories (WebDab, 2006). Also our calculations for Asia are consistent with the numbers that have been officially reported by major Asian countries, as well as with the estimates by Streets *et al.*, 2003.

However, there are significant discrepancies between our assessment of SO_2 emissions and the EDGAR global emission inventory (RIVM, 2005), which suggests for the year 2000 more than 10% higher emissions globally (Table 2). Based on our detailed accounting of the emission control measures that have been put into operation after 1990, we identify the omission of this effect in the EDGAR inventory as the main reason for the discrepancies. In contrast, our global estimates of NO_x and CO, for which fewer control measures have been introduced before 2000, differ from EDGAR by only 4-5%. Inventories for individual countries and economic sectors show larger differences. EDGAR tends to estimate higher emissions from industry and the domestic sector, and lower emissions from transport, especially from non-road sources.

Early estimates of global BC and OC emissions show large variations (Table 3), essentially due to significant differences in the applied emission factors (Bond *et al.*, 2004). Compared to the recent inventory of Bond *et al.*, 2004, we obtain 10 to 15% higher estimates for BC and OC emissions, mainly as a result of the different representation of emission sources and their activities that emerged from the incorporation of national statistics.

Our CH_4 estimates and the national data reported to UNFCCC typically diverge by 10 to 20%, owing to different methodological approaches. Comparisons with other global studies (US-EPA, 2005; Nakicenovic *et al.*, 2000; RIVM, 2005) show differences below 10%. Also our regional estimates correspond well with other inventories, although we calculate lower emissions from rice cultivation and wastewater treatment, and higher emissions from solid waste landfills.

4.2 Emission projections

Sulfur dioxide

As a consequence of continuing implementation of emission control measures as prescribed in national legislation, we calculate for global anthropogenic emissions of SO_2 a 30% decline between 1990 and 2010, and stabilization thereafter despite increasing coal use (Table 4). However, trends exhibit significant differences across world regions. Emissions in Asia are expected to grow by a factor of two to three due to the large increase in coal use for power generation without adequate pollution control. Continued growth also applies to Chinese emissions until 2010, unless the more stringent emission controls that have been recently proposed should materialize (SEPA, 2004). With the exception of Africa, SO_2 emissions in all other regions should decline by between 40% and 80%.

A comparison of our emission estimates with the SO_2 trajectories of the two SRES (MESSAGE) scenarios (Nakicenovic *et al.*, 2000) shows broadly consistent results for the year 1990. However, as in the EDGAR inventory, the SRES figure for 2000 is more than 30% higher than our number, essentially because some of the emission control measures that have been installed before 2000 are not considered in the SRES estimates that were published in 2000. In addition, there is uncertainty about the level of coal consumption in China in the year 2000 (Akimoto *et al.*, 2006), for which the SRES scenarios assume higher volumes than our study. Future estimates of SO_2 emissions depend critically on the SRES pathway of economic development. In 2030, SRES figures exceed our "current legislation" assessment for the A2 scenario by 100%, while they are in agreement for the B1 scenario.

Technologies are available today that, if fully implemented, could reduce global SO_2 emissions by more than 80 percent compared to the 1990 level. The scope for further reductions, however, depends on the stringency of the already implemented measures and differs greatly among countries. While our analysis shows a limited potential for the industrialized countries, there remains significant scope for further reductions in many developing countries.

Nitrogen oxides

We find that (pollution control) technology will have a dominating impact on the levels of future NO_x emissions. All economic projections foresee a continuing increase in economic wealth accompanied by strong growth in vehicle mileage and freight transport volumes. For instance, scenarios assume growth in transport demand by a factor of four to five for Asia. However, today most Asian countries have emission control legislation for vehicles already in place that, if fully implemented, would limit the growth in Asian NO_x emissions by 2030 to not more than 45-50% from today's levels. Latin American emissions should stabilize if current legislation were fully implemented. In the absence of legal control requirements, African emissions would more than double. In contrast, according to our estimates the latest legislation in the OECD region should lead to a 45% cut in NO_x by 2030 (Table 5). Thereby, at the global level, the rise in NO_x

emissions from developing countries would be offset by the decline in the OECD and in Eastern and Central Europe, so that we do not expect major changes in total anthropogenic NO_x emissions by 2030.

The incorporation of emission control legislation that has been adopted during the last decade in many countries in Asia, Latin America, Eastern Europe and Russia leads to significantly lower emission projections compared to earlier studies that have neglected this development. For instance, with comparable growth rates in the vehicle stock and constant 1990 emission factors, the SRES scenarios proposed an increase in global anthropogenic NO_x emissions between 65% and 95% by 2030.

If fully implemented, currently available technologies could reduce global NO_x emissions by another 60 percent below our "current legislation" case.

Carbon monoxide

Our analysis suggests for most world regions a continuing decline of CO emissions, resulting in 27% less global emissions by 2030 (Table 6). This decoupling between economic growth and CO emissions is related to the declining use of coal and fuel wood in domestic small stoves and to the penetration of three-way catalysts that drastically reduce CO emissions from vehicles. Especially large reductions should occur in Latin America (54%) from the anticipated substitution of fuel wood by other forms of energy in the residential sector. In contrast, there is little reason to believe that emissions in Africa should not growth further.

Our projections of future CO emissions arrive at significantly lower figures than earlier studies that have not considered the control measures implemented after the mid-1990's.

As for the other pollutants, current legislation does not exhaust the full reduction potential that is offered by today's available technological measures. For 2030, we estimate that it would be technically possible to reduce global anthropogenic CO emissions by half compared to current levels, and that there is additional potential from an accelerated phase-out of solid fuels in the domestic sector.

Primary carbonaceous particles

With current legislation, our baseline scenario results in a 17% decline in global anthropogenic BC emissions by 2030 (Table 7), mainly due lower consumption of coal and the replacement of traditional stoves in the domestic sector as well as from the controls applied to mobile sources (Figure 2). For OC, we obtain an even larger reduction of 35% for the year 2030.

The important influence of technology on future levels of carbonaceous particles from anthropogenic sources is illustrated in our "maximum technically feasible reduction" scenario, which suggests for 2030 a lower bound on global emissions at 50 to 60% below the 2000 levels. Largest reductions are possible in the transport sector (especially for BC), for small-scale residential combustion sources and through a ban on the open burning of crop residues. The reduction potential varies greatly between regions. For instance, only small reductions are possible in Africa and South-east Asia, where many of the traditional appliances will remain in use up to 2030.

Methane

The absence of widespread mitigation policies together with the economic growth projected for 2030 results for methane (CH_4) in approximately 50% higher emissions than in 2000 (Table 9). Increases are expected from all sectors except from the use of solid biomass for energy purposes. Our projections are rather consistent with the IPCC SRES assessment (Nakicenovic *et al.*, 2000), lying well within the range spanned by the SRES scenarios A2 and B2.

A wide range of technical measures is presently available to reduce CH_4 emissions (Höglund-Isaksson, 2005) that could reduce, if fully implemented, global anthropogenic CH_4 emissions in 2030 by 30% compared with 2000.

5. Discussion and conclusions

This paper explores the possible future range of global emissions of air pollutants based on two sets of emission control scenarios. Both scenarios rely - to the maximum possible extent - on national projections of future economic, energy and agricultural activities. They focus on the next three decades, and are therefore immediately relevant for today's policy decisions.

Our analysis demonstrates that it is technically possible to decouple economic development and air pollution also at the global scale. Inevitably, population growth and economic development will lead to higher volumes of human activities. New technologies, however, will be cleaner and will cause less pollution, certainly per unit of anthropogenic activity. If we combine our expectations on future economic development with the technical performance of pollution control equipment and the currently adopted timetables for its implementation, we find that global emissions of air pollutants will grow at a much lower pace than earlier thought, and in several cases might even decline in the future. This will not only occur in industrialized countries. Spurred by concern about local air quality, many developing countries have recently adopted increasingly stringent emission control legislation, which will reduce the previously uncontrolled growth in air pollution in those countries.

According to our analysis, global SO_2 emissions decreased in the 1990s by more than 20%, and current energy and air pollution control policies should lead to a further decline. However, unless stricter controls are enforced, emissions might start to increase again after 2020. The new legislation for mobile sources that has been adopted in many developing countries in Asia and Latin America after the year 2000 will lead to substantially lower growth rates in emissions of NO_x and CO from the transport sector compared to what was suggested in earlier studies. Overall, these recent changes in developing countries and the adoption of even more stringent emission standards in the OECD and the Central and Eastern European countries make strong increases of global emissions of NO_x and CO unlikely in the coming decades. Based on our assessment, global NO_x emissions should remain below current levels until 2030. In contrast to some of the previous estimates we calculate decreases of global anthropogenic BC and OC emissions by 2030 of nearly 20 and 35%, respectively. Major drivers behind this development are the phase-out of solid fuels in the residential sector, improvements in combustion technology, and stringent emission standards on mobile sources. However, for methane, which has been seen in the past mainly in its role as a potent greenhouse gas, the absence of targeted mitigation strategies would still allow an increase in global emissions of 50% by 2030.

Obviously, these emission scenarios are associated with important uncertainties, ranging from the general imponderability about future economic development to the incomplete knowledge of current emission factors in developing countries. Most critical, however, is the question to what degree and how efficiently the legally required emission control measures will be implemented. Assuming full compliance with current national legislations, our projections suggest for most pollutants significantly lower emissions than earlier studies that have not considered these recent policy developments. Doubts have been expressed about the effectiveness of the implementation of current legislation, both in industrialized and developing countries. Thus, an emission projection assuming serious implementation failures of the current legal requirements would obviously result in significantly higher emissions. However, there is clear evidence that economic and social development increases public concern about local air quality, and creates stronger pressure for efficient mitigation measures and on actual compliance. This concern is now rapidly spreading also in many developing countries. From such a perspective, compliance with - at least - today's legal requirements might be a reasonable assumption for the year 2030 when many developing countries will have reached much higher levels of economic development. Furthermore, since our analysis shows that current measures will not be sufficient to reduce – and in many case not even maintain - current emission levels in developing countries, further strengthening of legislation could be seen as a not implausible scenario.

Our analysis also shows ample technical scope for further reductions of air pollutant emissions through more widespread application of today's available emission control technologies. Although at high costs, such measures could reduce global SO_2 emissions by up to 77%

compared to 2000, NO_x emissions by 64%, CO and BC emissions by 50%, OC by 60%, and CH_4 by 30%.

While our analysis results in a more optimistic picture about future emissions from anthropogenic land-based emissions than earlier assessments, one should not lose sight of other sources that make significant – and ever increasing – contributions to global pollution. Although not part of this paper, available literature indicates continued increases in the emissions from marine shipping (e.g., Derwent *et al.*, 2005) and from aviation, which might counteract costly efforts to reduce the impacts of air pollution from land-based sources.

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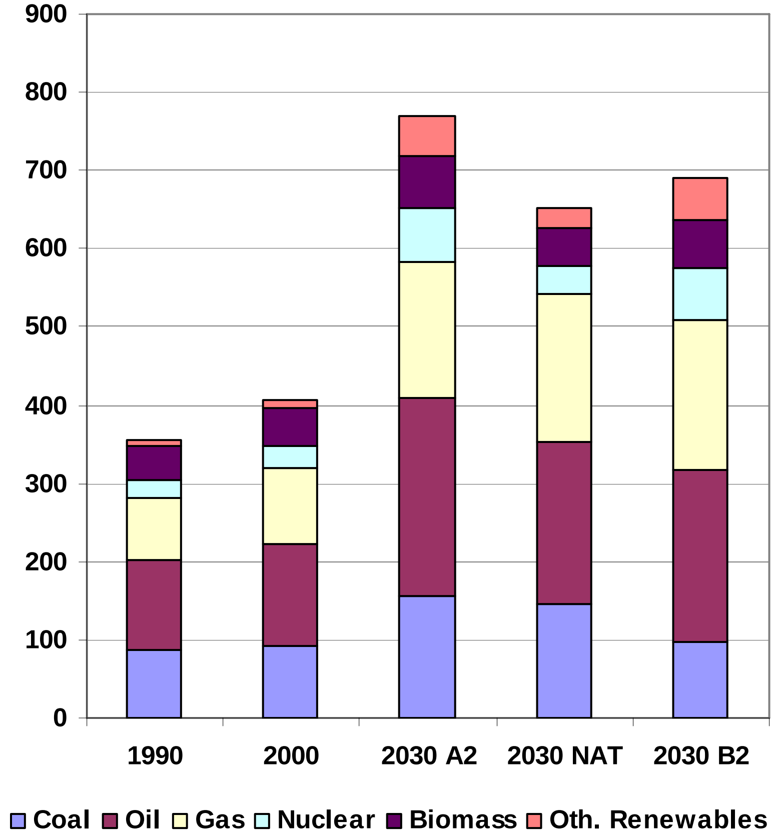

Figure 1: Global energy demand by fuel type (in 10^{18} J) for 1990, 2000 and three projections for 2030: the national energy projections (NAT), and the SRES A2 and SRES B2 scenarios.

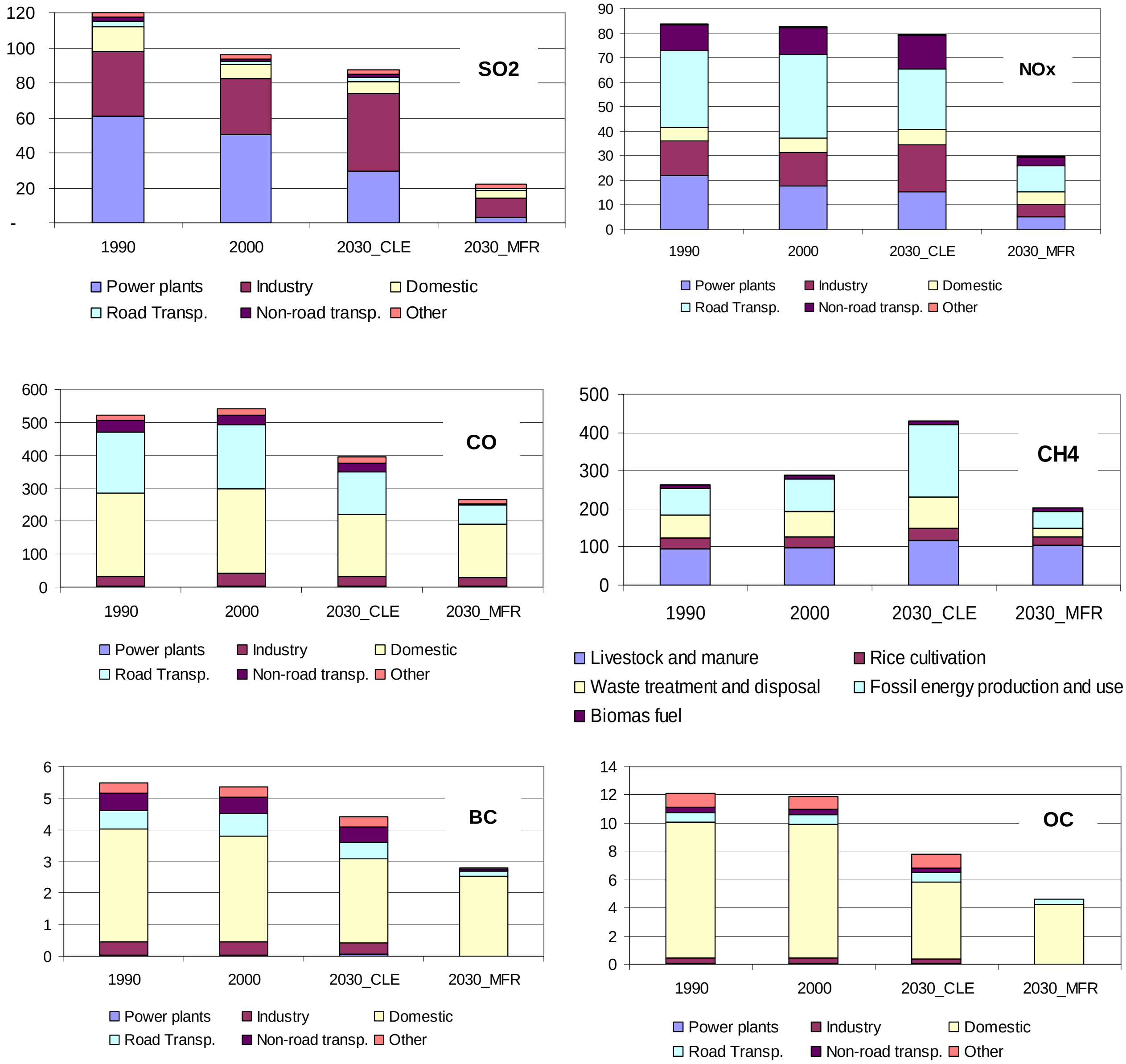

Figure 2: Projected development of global anthropogenic emissions by economic sector for SO_2, NOx, CO, CH_4 (Tg a^{-1}), and carbonaceous particles (BC and OC, Tg C a^{-1}). Estimates for historic years (1990 and 2000) and for 2030 for the “current legislation” (2030_CLE) and the “maximum technically feasible reductions” (2030_MFR) cases.

Table 1: Population, GDP and energy consumption by world region

Region	1990	2000	2030		
			SRES A2	National projections	SRES B2
Population, million					
OECD	859	916	1072	1040	994
Central and Eastern Europe	413	415	473	410	416
Asia	2798	3248	4779	4288	4312
Africa and Latin America	1192	1511	2846	2649	2649
World	5262	6090	9170	8388	8371
GDP, Trillion US $1990[a]					
OECD	16.4	21.1	30.0	44.7	33.1
Central and Eastern Europe	1.1	1.0	2.1	2.8	2.8
Asia	1.5	3.5	7.6	19.0	21.3
Africa and Latin America	1.9	2.7	11.5	8.8	8.8
World	20.9	28.3	51.2	75.4	66.0
Energy consumption, EJ					
OECD	167	193	277	257	249
Central and Eastern Europe	69	49	85	66	73
Asia	72	99	225	204	240
Africa and Latin America	48	65	181	124	127
World	356	407	769	652	689

[a] At market exchange rates

Table 2: Emission estimates by world region for air pollutants and methane for the year 2000. Results from this study compared with the EDGAR inventory [Tg year^{-1}].

	OECD		Central and Eastern Europe		Asia		Africa and Latin America		WORLD	
	This study	EDGAR	This study	EDGAR	This study	EDGAR	This study	EDGAR	This study	EDGAR
NOx	37	34	9	11	22	28	15	17	83	90
SO_2	29	36	16	24	32	54	18	24	96	138
CO	133	125	28	44	236	221	145	141	542	531
CH_4	54	71	51	43	134	119	71	77	310	309

Table 3: Comparison of global emission estimates for BC and OC, Gg C a^{-1}.

Source	Year	BC	OC
Penner et al. (1993)	1980	12610	-
Cooke and Wilson (1993)	1984	7970[a]	-
Cooke et al. (1999)	1984	5100[a]	7000[a]
Bond et al. (2004) [b]	1996	9478	28455
Bond et al. (2004) [c]	1996	4954 (3296-11019)	10423 (5925-20992)
This study	1995 / 2000	5551 / 5342	12143 / 11842

[a] Emissions from fossil fuel use.

[b] Activity as in Bond et al (2004) while emission factors from Cooke et al. (1999). Includes open burning of crop residues.

[c] Totals adjusted to include open burning of crop residue for which ranges estimated from ranges given for total open burning.

Table 4: Anthropogenic emissions of SO_2 by world region (Tg SO_2 a^{-1}).

Regions of the SRES study	1990	2000	Current legislation (CLE) 2010	2020	2030	Maximum feasible reductions (MFR) 2010	2020	2030
OECD90:	45	29	18	14	13	5	5	5
North America	24	19	11	8	8	3	3	3
Western Europe	18	8	4	3	3	1	1	1
Pacific OECD	3	3	3	3	3	1	1	1
REF:	30	16	11	8	8	2	2	2
Central and Eastern Europe	11	6	4	2	2	1	0	0
Russia and NIS	19	10	7	6	6	2	2	2
Asia:	31	32	41	46	53	10	11	11
Centrally Planned Asia	21	21	25	22	22	6	6	6
Other Pacific Asia	5	4	6	7	9	2	2	2
South Asia	5	7	11	17	22	2	3	3
ALM:	15	18	15	14	13	4	4	4
Latin America	7	8	6	5	5	2	2	2
Middle East	3	5	3	3	2	1	1	1
Africa	5	5	5	5	6	1	1	2
World Total	120	96	85	82	87	21	22	22
SRES (A1 Message)	130	126	120	113	112	-	-	-
SRES (A2 Message)	130	126	125	148	177			
SRES (B1 Message)	130	126	120	99	84			
SRES (B2 Message)	130	126	120	111	109	-	-	-

Table 5: Anthropogenic emissions of NO_x by world region (Tg NO_2 a^{-1}).

Regions of the SRES study	1990	2000	Current legislation (CLE) 2010	2020	2030	Maximum feasible reductions (MFR) 2010	2020	2030
OECD90:	42	37	29	21	20	10	10	11
North America	24	22	18	12	12	6	6	7
Western Europe	15	11	8	6	6	3	3	3
Pacific OECD	4	4	3	3	3	1	1	1
REF:	14	9	8	7	8	2	2	2
Central and Eastern Europe	3	2	2	1	1	1	0	1
Russia and NIS	11	7	6	5	6	1	2	2
Asia:	15	22	27	29	32	8	10	11
Centrally Planned Asia	8	11	14	14	15	4	5	5
Other Pacific Asia	4	6	6	6	7	2	2	3
South Asia	3	6	7	9	10	2	3	3
ALM:	12	15	13	15	19	3	4	5
Latin America	6	7	6	7	8	2	2	2
Middle East	3	4	3	3	4	1	1	1
Africa	3	4	4	5	8	1	1	2
World Total	84	83	78	71	80	24	26	30
SRES (A1 Message)	82	86	110	144	180	-	-	-
SRES (A2 Message)	82	86	106	136	165			
SRES (B1 Message)	82	86	106	124	136			

SRES (B2 Message)	82	86	102	121	143	-	-	-

Table 6: Anthropogenic emissions of CO by world region (Tg CO a^{-1}).

			Current legislation (CLE)			Maximum feasible reductions (MFR)		
Regions of the SRES study	1990	2000	2010	2020	2030	2010	2020	2030
OECD90:	157	133	86	74	74	46	50	53
North America	91	84	53	46	47	26	29	32
Western Europe	55	38	23	21	21	16	17	17
Pacific OECD	11	12	9	8	7	5	5	5
REF:	42	28	25	21	23	12	13	14
Central and Eastern Europe	8	7	5	4	4	3	3	2
Russia and NIS	33	20	19	17	19	9	11	12
Asia:	191	236	211	171	171	147	133	133
Centrally Planned Asia	98	136	117	90	89	78	69	67
Other Pacific Asia	31	38	38	28	30	21	20	22
South Asia	62	61	56	53	52	48	45	43
ALM:	134	145	127	128	125	78	77	65
Latin America	69	57	39	30	26	22	19	14
Middle East	11	15	7	7	10	3	4	5
Africa	55	74	82	91	90	53	55	46
World Total	523	542	449	395	394	282	274	266
SRES B2 (Message)	399	402	467	561	671	-	-	-
SRES A2 (Message)	399	402	504	639	806	-	-	-

Table 7: Anthropogenic emissions of black carbon (BC) by world region (Tg C a^{-1}).

			Current legislation (CLE)			Maximum feasible reductions (MFR)		
Regions of the SRES study	1990	2000	2010	2020	2030	2010	2020	2030
OECD90:	0.8	0.8	0.6	0.5	0.4	0.3	0.3	0.2
North America	0.3	0.3	0.2	0.2	0.2	0.1	0.1	0.1
Western Europe	0.4	0.4	0.3	0.2	0.2	0.2	0.2	0.1
Pacific OECD	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0
REF:	0.7	0.3	0.3	0.3	0.3	0.2	0.1	0.1
Central and Eastern Europe	0.1	0.1	0.1	0.1	0.0	0.1	0.0	0.0
Russia and NIS	0.5	0.2	0.3	0.2	0.3	0.1	0.1	0.1
Asia:	3.1	3.3	3.5	3.1	2.9	2.5	2.2	1.9
Centrally Planned Asia	2.0	2.2	2.4	2.2	1.9	1.7	1.5	1.3
Other Pacific Asia	0.3	0.4	0.4	0.3	0.3	0.2	0.2	0.2
South Asia	0.7	0.8	0.7	0.7	0.7	0.5	0.4	0.4
ALM:	0.9	1.0	1.0	0.9	0.8	0.7	0.7	0.5
Latin America	0.5	0.4	0.3	0.3	0.2	0.2	0.2	0.1
Middle East	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Africa	0.3	0.5	0.6	0.6	0.5	0.5	0.5	0.4
World Total	5.5	5.3	5.4	4.8	4.4	3.7	3.2	2.8

Table 8: Anthropogenic emissions of organic carbon (OC) by world region (Tg C a^{-1}).

			Current legislation (CLE)			Maximum feasible reductions (MFR)		
Regions of the SRES study	1990	2000	2010	2020	2030	2010	2020	2030
OECD90:	1.2	0.9	0.8	0.7	0.7	0.5	0.4	0.4
North America	0.4	0.4	0.3	0.3	0.3	0.1	0.1	0.1
Western Europe	0.6	0.5	0.4	0.4	0.3	0.3	0.3	0.2
Pacific OECD	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0
REF:	1.2	0.6	0.6	0.5	0.5	0.2	0.2	0.2
Central and Eastern Europe	0.3	0.2	0.1	0.1	0.1	0.1	0.1	0.1
Russia and NIS	0.7	0.3	0.4	0.4	0.4	0.1	0.1	0.1
Asia:	7.1	7.6	7.3	5.7	4.6	3.2	2.8	2.6
Centrally Planned Asia	4.2	4.8	4.7	3.8	3.0	2.0	1.8	1.6
Other Pacific Asia	0.9	0.9	0.9	0.6	0.6	0.4	0.3	0.4
South Asia	2.0	1.9	1.7	1.3	1.0	0.8	0.7	0.7
ALM:	2.7	2.8	2.7	2.5	1.9	2.1	2.0	1.5
Latin America	1.4	1.0	0.8	0.6	0.4	0.5	0.4	0.2
Middle East	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Africa	1.2	1.7	1.9	1.9	1.5	1.6	1.6	1.3
World Total	11.9	11.8	11.4	9.4	7.7	6.0	5.4	4.7

Table 9: Anthropogenic emissions of CH_4 by world region (Tg CH_4 a^{-1}).

CH4:			Current legislation (CLE)			Maximum feasible reductions (MFR)		
Regions of the SRES study	1990	2000	2010	2020	2030	2010	2020	2030
OECD90:	55	56	56	58	60	31	32	33
North America	24	26	28	30	32	12	13	14
Western Europe	22	19	18	18	17	14	13	13
Pacific OECD	9	10	10	11	11	6	6	6
REF:	48	42	41	45	48	16	16	17
Central and Eastern Europe	9	7	6	6	7	4	4	4
Russia and NIS	39	35	35	38	41	12	12	13
Asia:	91	105	120	135	149	69	74	81
Centrally Planned Asia	43	49	56	63	68	26	29	31
Other Pacific Asia	16	20	24	29	35	12	13	15
South Asia	32	35	39	43	47	31	32	35
ALM:	58	74	92	119	160	52	60	72
Latin America	30	34	40	48	55	27	30	33
Middle East	8	14	20	30	49	6	8	13
Africa	20	27	33	41	56	19	22	26
World Total	252	277	309	357	417	167	182	203
SRES B2 (Message)	269	297	346	404	466	-	-	-
SRES A2 (Message)	269	297	325	364	406	-	-	-