GAINS
ASIA

SCENARIOS FOR COST-EFFECTIVE CONTROL OF AIR POLLUTION AND GREENHOUSE GASES IN CHINA

Markus Amann, Jiang Kejun, Hao Jiming, Shuxiao Wang, Zhuang Xing, Wei Wei, Deng Yi Xiang, Liu Hong , Xing Jia and Zhang Chuying, Imrich Bertok, Jens Borken, Janusz Cofala, Chris Heyes, Lena Höglund, Zbigniew Klimont, Pallav Purohit, Peter Rafaj, Wolfgang Schöpp, Geza Toth, Fabian Wagner, Wilfried Winiwarter

November 2008

IIASA ERI TSINGHUA UNIVERSITY 1911 teri ies Institute for Environment and Sustainability SIXTH FRAMEWORK PROGRAMME

The GAINS-Asia model integrates a number of established economic and environmental models developed by international experts at the following institutions:

IIASA
International Institute for Applied Systems Analysis
Laxenburg, Austria

ERI
Energy Research Institute
Beijing, China

TERI
The Energy and Resources Institute
Delhi, India

JRC-IES
Institute for Environment and Sustainability of the Joint Research Centre of the European Union
Ispra, Italy

UBERN
The University of Bern
Bern, Switzerland

The research was funded by
The Sixth Framework Program (FP6)
of the European Union.

Further information:

GAINS
International Institute for
Applied Systems Analysis (IIASA)
Schlossplatz 1
A-2361 Laxenburg
Austria

Tel: +43 2236 807
Email: rainsinfo@iiasa.ac.at
Web: http://gains.iiasa.ac.at

Executive Summary

Current economic growth will counteract ongoing efforts to improve air quality problems in China unless pollution control laws are significantly upgraded.

Current and future economic growth in China will counteract ongoing efforts to improve air quality through controls of sulphur dioxide (SO_2) emissions from large stationary sources and nitrogen oxide (NO_x) emissions from vehicles. Unless further air pollution policies are implemented, the increase in coal consumption to fuel additional industrial production and provide more electricity to a wealthier population will largely compensate the positive effects of current efforts to control SO_2 emissions in China. The lack of regulations for controlling emissions of NO_x from large stationary sources is expected to lead to a 30% increase in China's NO_x emissions, despite the tight emission control legislation that has been recently imposed on mobile sources. Consequently, without further air pollution control policies, negative impacts on human health and vegetation that are currently felt across China will not substantially improve in the coming decades. For instance, it is estimated that present exposure to fine particulate matter (PM2.5) is shortening life expectancy of the Chinese population by approximately 40 (21-53) months, and it would in a business-as-usual case remain at that level for the coming decades. Emissions of greenhouse gases that contribute to global climate change would increase by approximately 80% by 2030.

Advanced emission control technologies are available to maintain acceptable levels of air quality despite the pressure from growing economic activities.

Yet, advanced emission control technologies are available to maintain acceptable levels of air quality despite the pressure from growing economic activities. Full application of advanced technical end-of-pipe emission control measures in China would lead to substantial improvements in air quality. It is estimated that negative health impacts could be reduced by 43% by 2030 by applying such advanced emission control technology to all large sources in China. However, such an undifferentiated across-the-board approach would impose significant burdens on the economy, involving an additional expense of 0.63% of GDP.

A cost-effective strategy can reduce costs for air pollution control by up to 80% compared to conventional approaches.

The GAINS (Greenhouse gas – Air pollution Interactions and Synergies) model can identify cost-effective portfolios of emission control measures that achieve improvements in environmental impacts at least cost. A cost-effective emission control strategy developed with the GAINS optimization tool, which selectively allocates specific reduction measures across economic sectors, pollutants and regions, would achieve equal air quality improvements at only 20% of the costs of a conventional across-the-board approach. An integral element of such an air pollution control strategy will be measures to eliminate indoor pollution from the combustion of solid fuels. The investment will also reduce crop losses by around 50% and have far-ranging positive impacts on the environment, but will not result in positive side-effects on greenhouse gas emissions.

A smart mix of measures that includes actions to reduce energy consumption can further cut air pollution control costs, and achieve lower greenhouse gas emissions.

Well-designed air pollution control strategies can also reduce emissions of greenhouse gases. GAINS demonstrates that low carbon strategies result in lower emissions of SO_2, NO_x and PM at no additional costs. GAINS estimates that each percent of CO_2 reduction will typically reduce health impacts from fine particulate air pollution by 1%.

This also means that, for achieving given targets on ambient air quality, the cost of air pollution can be further reduced by adopting certain low carbon measures. A GAINS scenario demonstrates that the additional costs of some climate-friendly measures, e.g., energy efficiency improvements, co-generation of heat and power, fuel substitution, integrated coal gasification combined cycle (IGCC) plants, etc., are more than compensated for by savings in air pollution control equipment. By selecting a smart mix of measures to simultaneously cut air pollution and greenhouse gas emissions, China can almost halve air pollution control costs as well as lower greenhouse gas emissions by 8%.

For policymakers, industry, NGOs and researchers wishing for more information and to conduct independent analyses, the GAINS-Asia model and documentation are freely available online at http://gains.iiasa.ac.at

Table of Contents

1 Introduction 5

2 Emissions and air quality impacts in 2005 7

2.1.1 An Emission inventory for 2005 7

2.2 Air quality 13

2.2.1 Ambient concentrations of PM2.5 13

2.2.2 concentrations of ground-level ozone 15

2.3 Air quality impacts 15

2.3.1 Health Impacts from outdoor pollution 15

2.3.2 Health impacts from indoor pollution 17

2.3.3 Crop losses from Ground-level ozone 18

3 The baseline projection up to 2030 19

3.1 Macro-economic development and energy consumption 19

3.2 Baseline projections for air pollution emissions 21

3.3 Baseline projections of air quality and health impacts 25

4 Alternative policy scenarios 29

4.1 Uniform application of advanced emission control technologies for large sources. 29

4.2 Cost-effective allocation of end-of-pipe air pollution controls 35

4.3 Cost-effective air pollution reductions including structural changes 41

4.4 Air pollution control through greenhouse gas mitigation strategies 45

5 Conclusions 49

About the authors

This report is the result of cooperation between scientists at the International Institute for Applied Systems Analysis (IIASA) in Laxenburg, Austria, the Energy Research Institute (ERI) in Beijing, China, and the Tsinghua University, Beijing, China.

At IIASA, the work was carried out by a team of IIASA's Atmospheric Pollution and Economic Development programme, led by Markus Amann. Team members include Imrich Bertok, Jens Borken, Janusz Cofala, Chris Heyes, Lena Hoglund, Zbigniew Klimont, Pallav Purohit, Peter Rafaj, Wolfgang Schöpp, Geza Toth, Fabian Wagner and Wilfried Winiwarter.

The team at ERI, led by Jiang Kejun, included Deng Yixiang and Zhuang Xing.

At Tsinghua University, the team was led by Hao Jiming and Wang Shuxiao and included Wei Wei, Xing Jia and Zhang Chuying.

1 Introduction

Since the 1980s China has experienced rapid economic development with average growth rates of 9.8 percent/year (ADB, 2007). The Chinese government aims at a continuation of the rapid economic development in the next decades, striving for an increase in per-capita income by a factor of five (in Market Exchange Rates) up to 2030. Thereby, total GDP would grow by a factor of six, given that the population is likely to increase to almost 1.5 billion people. These trends would transform China into one of the largest economies in the world. Even under the assumption that the envisaged growth in economic output will decouple from the growth in energy consumption, current projections suggest a doubling of Chinese energy consumption up to 2030 (IEA, 2007). Unless effective countermeasures are taken, these trends will further intensify the pressure on the atmosphere at the local, regional and global scales.

It will be a formidable task for Asian policy makers to further advance human wellbeing through continued economic development while providing acceptable levels of air quality to the citizens and assuring sustainable conditions for vegetation and ecosystems. At the same time, the envisaged growth in Asian greenhouse gas emissions will seriously challenge efforts of the world community to control global climate change.

For a number of historic reasons, response strategies to air pollution and climate change are often addressed by different policy institutions. However, there is growing recognition that a comprehensive and combined analysis of air pollution and climate change could reveal important synergies of emission control measures (Swart *et al.*, 2004), which could be of high policy relevance. Insight into the multiple benefits of control measures could make emission controls economically more viable, both in industrialized and developing countries. While scientific understanding on many individual aspects of air pollution and climate change has considerably increased in the last years, little attention has been paid to a holistic analysis of the interactions between both problems (Barker *et al.*, 2007).

The Greenhouse gas – Air pollution Interactions and Synergies (GAINS) model has been developed as a tool to identify emission control strategies that achieve given targets on air quality and greenhouse gas emissions at least cost. GAINS considers measures for the full range of precursor emissions that cause negative effects on human health via the exposure of fine particles and ground-level ozone, damage to vegetation via excess deposition of acidifying and eutrophying compounds, as well as the six greenhouse gases considered in the Kyoto protocol. In addition, it also considers how specific mitigation measures simultaneously influence different pollutants. Thereby, GAINS allows for a comprehensive and combined analysis of air pollution and climate change mitigation strategies, which reveals important synergies and trade-offs between these policy areas. This state-of-the-art interdisciplinary model builds on a scientific tool that has already helped European governments slash air pollution across the continent without compromising economic development (Hordijk and Amann, 2007).

Under the EU Sixth Framework Programme on Research (FP6), an international team of research institutions has implemented the GAINS model for India and China. The research team, headed by the International Institute for Applied Systems Analysis (IIASA, Laxenburg, Austria), included the Chinese Energy Research Institute (ERI, Beijing, China), Tsinghua University (Beijing, China), The Energy and Resource Institute (TERI, Delhi, India), the Institute for Environment and Sustainability of the Joint Research Centre of the European Commission (IES-JRC, Ispra, Italy) and the University of Bern (Switzerland). The GAINS model with all databases is now freely accessible for interactive use at the Internet (http://gains.iiasa.ac.at).

This report presents a set of policy scenarios that explore cost-effective strategies for reducing health and vegetation impacts of poor air quality in China. As a starting point the report summarizes emissions and resulting air quality for the year 2005 as estimated by the GAINS model (Section 2). Adopting the projections of Chinese government on economic development up to 2030, Section 3 presents a baseline projection that outlines the likely development of emissions, air quality and health and vegetation impacts that would result from the full implementation of emission control measures as laid down in current Chinese legislation. Section 4 explores alternative emission control strategies for reducing air pollution impacts in the future. It examines the cost-effectiveness of (i) uniform application of advanced end-of-pipe emission control technologies to large sources, (ii) an optimized allocation of air pollution control measures that achieve the same environmental improvements at least cost, (iii) air pollution control strategies that also include structural changes in the energy system, and (iv) energy strategies that aim at reducing greenhouse gas emissions in China. Conclusions are drawn in Section 5.

This report focuses on the description of policy scenarios for China that have been developed with the GAINS-Asia model. The methodology of the GAINS-Asia model is documented in detail in a companion report (Amann *et al.*, 2008b) that is available at http://gains.iiasa.ac.at. Policy scenarios for India are presented in a parallel report (Amann *et al.*, 2008c). The interactive GAINS-Asia model is freely accessible on the Internet at http://gains.iiasa.ac.at.

2 Emissions and air quality impacts in 2005

2.1.1 AN EMISSION INVENTORY FOR 2005

Based on energy statistics and information on fuel quality, the GAINS model estimates that in 2005 China emitted 31.5 million tons of SO_2, 16.9 million tons of NO_x, 17.9 million tons of PM10 which 12.7 million are in the form of PM2.5, 12.8 million tons of NH_3 and 16.1 million tons of VOC into the atmosphere (Table 2.1).

For SO_2, almost 90 percent of total emissions originated from power generation and industrial energy combustion. 24 percent of NO_x emissions are estimated to emerge from mobile sources (10 percent from road traffic), while industrial sources contributed 43 percent and the power sector 27 percent. The largest sources of fine particles (PM2.5) were industrial plants (44 percent), while the domestic sector with its incomplete combustion of solid fuels, as the next largest source of fine particles, emitted 36 percent of PM2.5. Solid fuel combustion in households was also responsible for 70 percent of the anthropogenic emissions of volatile organic compounds, while NH_3 emissions were predominantly released from agricultural activities (Figure 2.1).

Table 2.1: Estimates of emissions of air pollutants from anthropogenic sources in China in 2005, by sector (kilotons)

SECTOR	SO_2	NO_x	PM2.5	PM10	NH_3	VOC
COMBUSTION IN ENERGY AND TRANSFORMATION INDUSTRIES	15643	4558	919	2611	0	127
NON-INDUSTRIAL COMBUSTION PLANTS	2110	861	4572	4965	88	11109
COMBUSTION IN MANUFACTURING INDUSTRY	12015	7275	4233	5870	4	246
PRODUCTION PROCESSES	1327	71	1447	1986	169	2399
EXTRACTION AND DISTRIBUTION OF FOSSIL FUELS AND GEOTHERMAL ENERGY	0	0	40	397	0	553
SOLVENT AND OTHER PRODUCT USE	0	0	0	0	0	4853
ROAD TRANSPORT	92	1728	293	321	22	2192
OTHER MOBILE SOURCES AND MACHINERY	314	2407	184	194	1	889
WASTE TREATMENT AND DISPOSAL	0	0	163	163	782	473
AGRICULTURE	28	26	875	1376	11779	1038
TOTAL	**31528**	**16926**	**12725**	**17883**	**12844**	**16069**

In 2005 industrial energy combustion accounted for almost 50 percent of anthropogenic CO_2 emissions in China, and power generation another 38 percent. The largest shares of CH_4

emissions originated from coal mining and agricultural activities, while agriculture emitted most of N_2O emissions (Table 2.2, Figure 2.2).

Table 2.2: Estimates of Chinese emissions of greenhouse gases from anthropogenic sources in 2005, by sector

SECTOR	CO_2 (Mt)	CH_4 (kt)	N_2O (kt)	All GHGs (Mt CO_2eq)
COMBUSTION IN ENERGY AND TRANSFORMATION INDUSTRIES	2391	53	35	2403
NON-INDUSTRIAL COMBUSTION PLANTS	283	1379	37	324
COMBUSTION IN MANUFACTURING INDUSTRY	2988	127	29	3000
PRODUCTION PROCESSES	31	13	11	34
EXTRACTION AND DISTRIBUTION OF FOSSIL FUELS AND GEOTHERMAL ENERGY	188	24097	0	694
SOLVENT AND OTHER PRODUCT USE	0	0	26	8
ROAD TRANSPORT	258	120	15	265
OTHER MOBILE SOURCES AND MACHINERY	169	13	6	171
WASTE TREATMENT AND DISPOSAL	0	11156	66	255
AGRICULTURE	0	19072	1629	905
TOTAL	**6308**	**56030**	**1854**	**8059**

Based on provincial energy statistics and fuel characteristics, emissions are estimated for each province (Table 2.3). In general, the GAINS emission estimates compare well with other inventories from national and international sources. Detailed comparisons are provided in Amann *et al.*, 2008b.

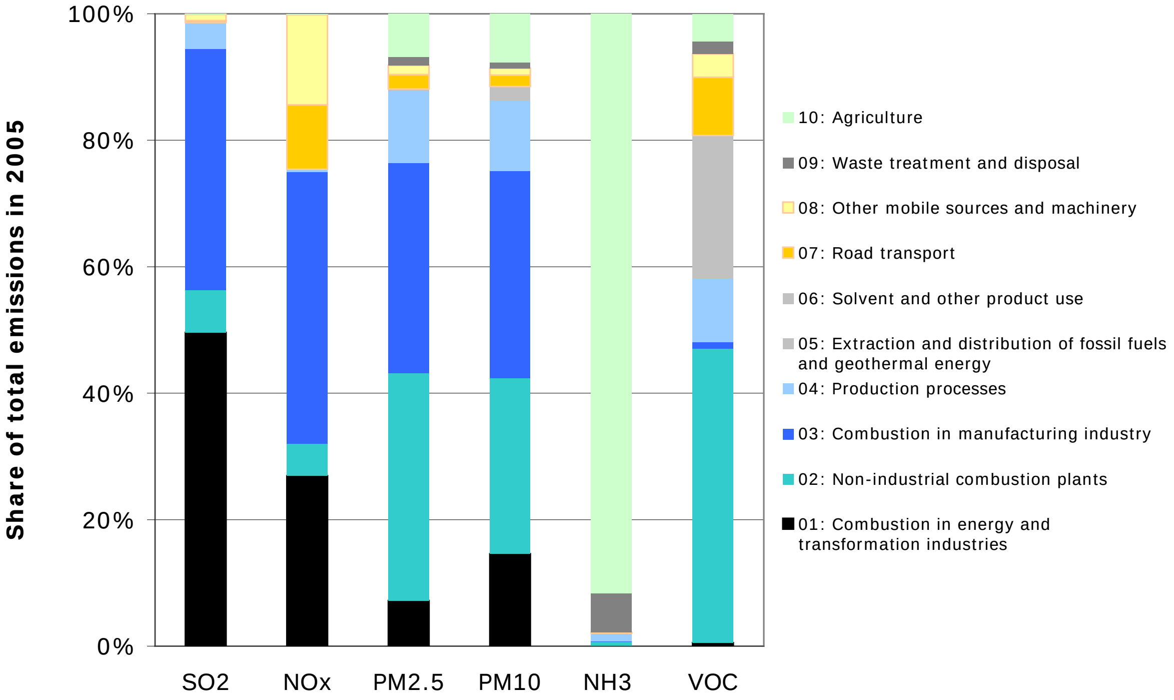

Figure 2.1: Contributions of source sectors to total anthropogenic emissions of air pollutants in China in 2005

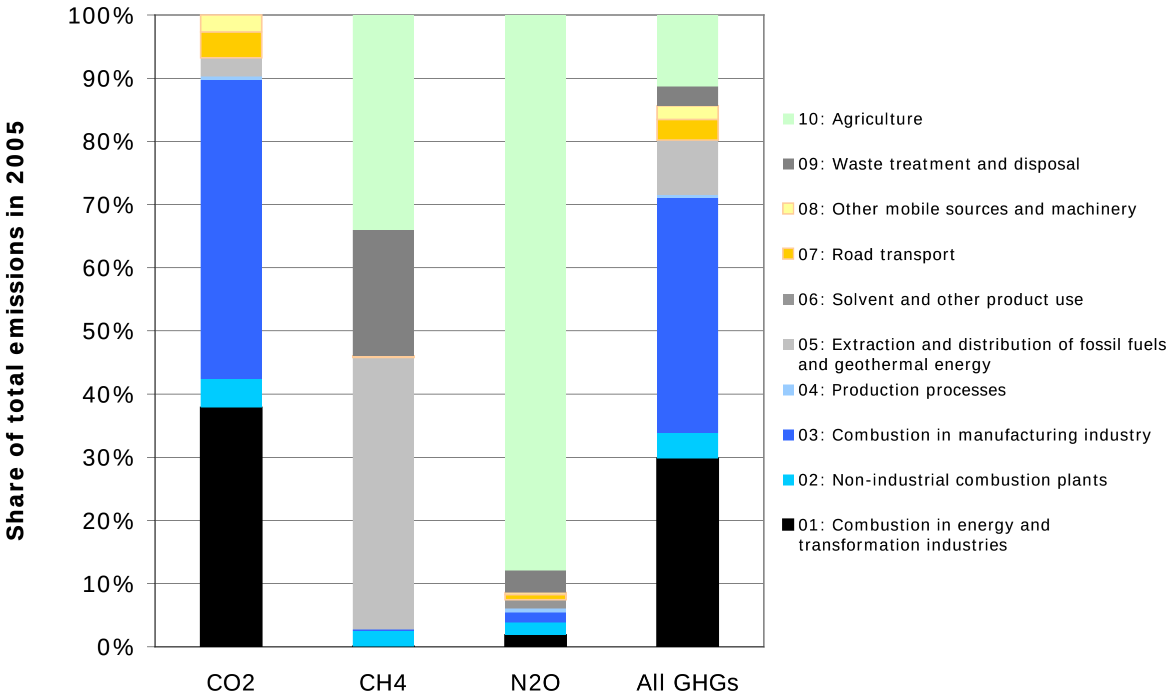

Figure 2.2: Contributions of source sectors to total anthropogenic emissions of greenhouse gases in China in 2005

Table 2.3: Emissions of air pollutants in 2005 by province (kilotons)

	SO_2	NO_x	PM2.5	PM10	NH_3	VOC
ANHUI	1143	753	614	817	600	1018
BEIJING	450	285	115	174	65	151
CHONGQING	928	308	217	302	242	247
FUJIAN	458	323	175	272	276	134
GANSU	371	279	214	296	249	289
GUANGDONG	1706	1022	638	929	588	750
GUANGXI	737	312	397	504	497	575
GUIZHOU	758	285	234	344	389	256
HAINAN	62	64	107	122	91	259
HEBEI	2211	1170	941	1318	844	884
HEILONGJIANG	460	555	404	560	397	802
HENAN	1638	876	815	1143	1109	880
HONG KONG	21	213	17	20	6	49
HUBEI	1288	688	597	780	622	847
HUNAN	745	425	452	610	667	536
I. MONGOLIA	518	375	355	476	308	603
JIANGSU	2179	1220	1007	1396	793	1281
JIANGXI	536	316	329	493	396	355
JILIN	1830	943	574	841	330	643
LIAONING	1221	559	321	526	319	348
NINGXIA	316	115	76	116	65	91
QINGHAI	74	71	53	71	103	62
SHAANXI	912	337	270	397	268	361
SHANDONG	1337	815	212	374	70	188
SHANGHAI	2791	1393	1137	1544	997	1508
SHANXI	1927	709	470	779	266	216
SICHUAN	1773	566	854	1048	867	1505
TIANJIN	537	568	120	171	47	222
TIBET XIZANG	4	9	14	25	151	17
XINJIANG	397	240	157	221	307	245
YUNNAN	447	300	319	440	605	332
ZHEJIANG	1752	831	524	772	312	413
TOTAL	**31528**	**16926**	**12725**	**17883**	**12844**	**16069**

Table 2.4: Emissions of greenhouse gases in 2005 by province

	CO_2 (Mt)	CH_4 (kt)	N_2O (kt)	all GHG (Mt CO_2eq)
ANHUI	277	2405	89	355
BEIJING	116	320	11	126
CHONGQING	114	1042	34	146
FUJIAN	124	865	35	153
GANSU	104	953	42	137
GUANGDONG	383	2191	71	451
GUANGXI	108	1629	57	160
GUIZHOU	117	1895	48	171
HAINAN	14	275	11	24
HEBEI	448	2266	122	533
HEILONGJIANG	213	2708	63	290
HENAN	347	3858	162	478
HONG KONG	39	76	2	41
HUBEI	249	1858	80	313
HUNAN	149	2715	81	232
I. MONGOLIA	147	1003	53	184
JIANGSU	504	1490	109	569
JIANGXI	120	1582	46	168
JILIN	375	1516	55	424
LIAONING	248	3576	59	341
NINGXIA	52	418	12	64
QINGHAI	26	366	20	40
SHAANXI	136	2317	43	198
SHANDONG	237	2163	14	287
SHANGHAI	520	1834	167	610
SHANXI	325	5995	44	464
SICHUAN	185	3579	125	298
TIANJIN	121	402	9	132
TIBET XIZANG	2	326	23	16
XINJIANG	84	1534	53	132
YUNNAN	111	1859	73	172
ZHEJIANG	314	1013	42	349
TOTAL	**6308**	**56030**	**1854**	**8059**

To put these figures into an international perspective, Figure 2.3 and Figure 2.4 compare, on a per-capita basis, estimates for China with data for the United States of America, the European Union and India. While Chinese per-capita emissions are significantly lower than those of the United States, they are close (for NH_3 and VOC) or higher (SO_2 and PM2.5) than the per-capita emissions of the European Union. In contrast, however, per-capita greenhouse gas emissions of the EU are higher than those of China, underlining the effects of air pollution control measures that are in place in Europe.

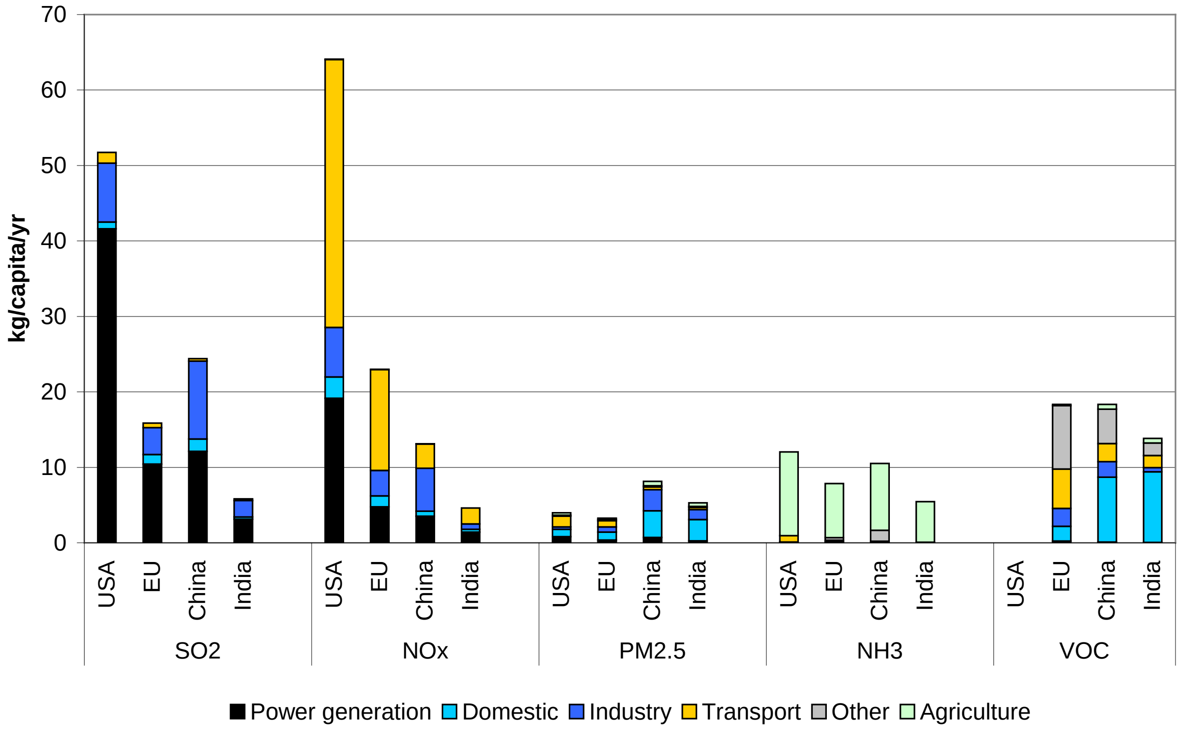

Figure 2.3: Per-capita emissions of air pollutants by sector in 2005

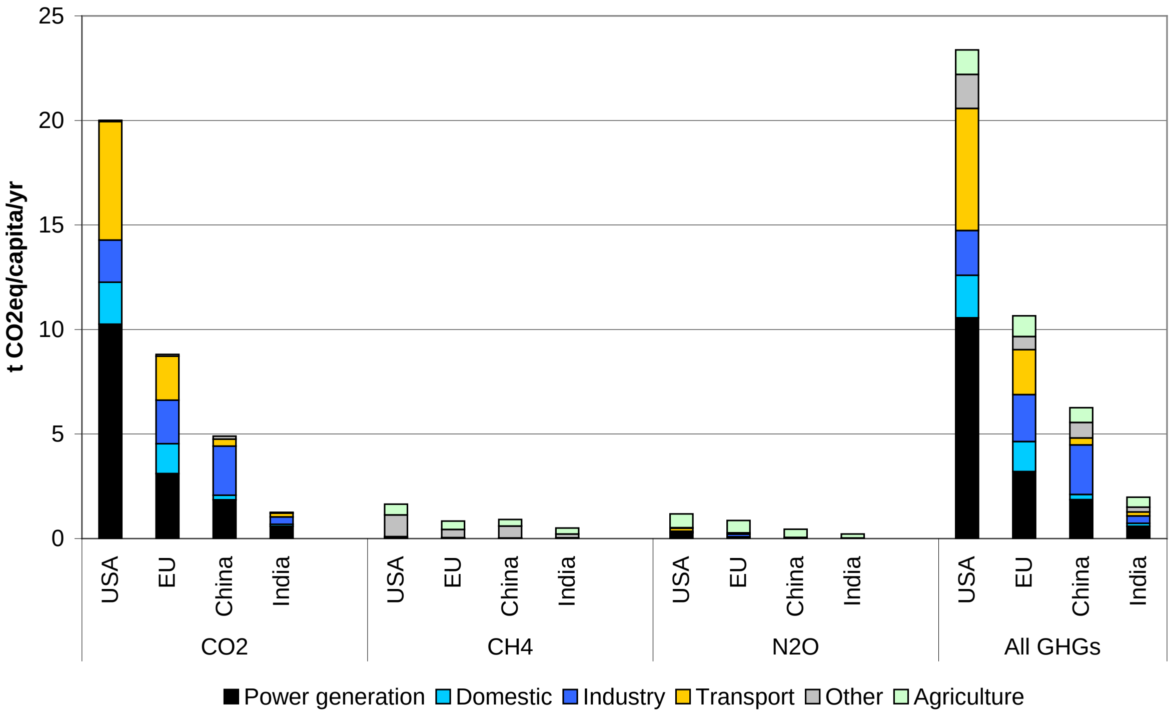

Figure 2.4: Per-capita emissions of greenhouse gases by sector in 2005

2.2 Air quality

For the emission inventory presented above, the GAINS model estimates air quality and resulting impacts on human health and environment.

2.2.1 AMBIENT CONCENTRATIONS OF PM2.5

Based on the detailed spatial and sectoral GAINS emission inventory, GAINS computes fields of ambient concentrations of PM2.5 with the help of source-receptor relationships derived from the TM5 model. The model computed contributions from (i) primary particulate matter released from anthropogenic sources, (ii) secondary inorganic aerosols formed from anthropogenic emissions of SO_2, NO_x and NH_3, (iii) particulate matter from natural sources (soil dust, sea salt, biogenic sources). The health impact assessment associates only anthropogenic sources with negative health impacts. Figure 2.5 displays annual mean concentrations of PM2.5 in ambient air computed for the emissions of 2005.

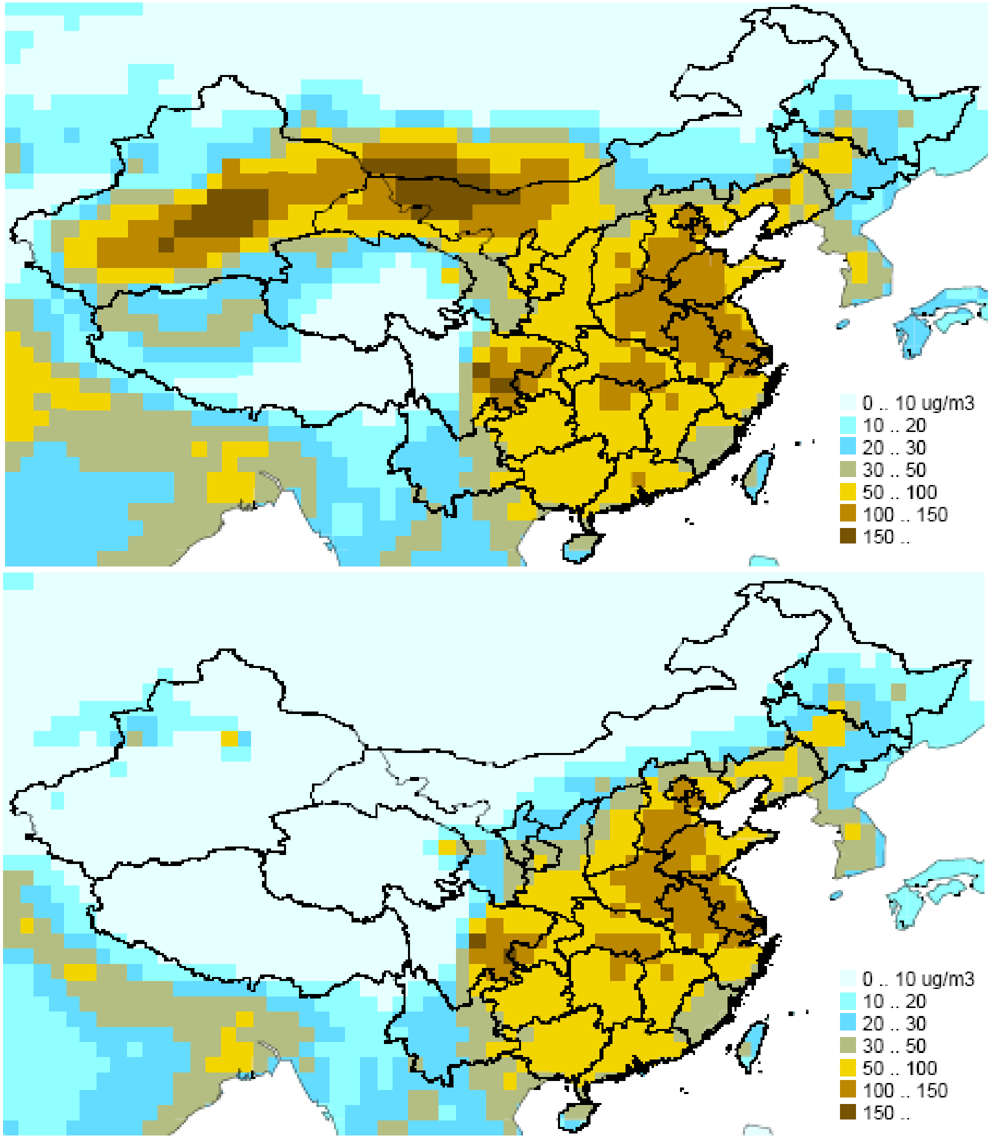

Figure 2.5: Ambient concentrations of PM2.5 computed for 2005. Top panel: all sources, bottom panel: PM2.5 only from anthropogenic emissions

The model-measurement comparison is shown in Figure 2.6. The small number of points in this graph and their quantised appearance indicate the relative scarcity of PM2.5 measurements suitable for the validation. The large spread in measured values corresponding to one GAINS estimate is caused by the use of data for different measurement locations and/or different years. The spread gives an indication of the variability in the measurements, all of which are compared with just one GAINS estimate for one grid cell.

The GAINS modelled estimate includes the basic average anthropogenic PM2.5 concentration for the relevant grid cell plus the calculated urban increment – if appropriate – plus an estimate of the fine fraction of the natural dust concentration. Although not perfect, the agreement with available measurements shows a reasonable match of GAINS estimates with the few available monitoring data for China. However, it should be pointed out that comparisons with measurements of individual PM2.5 components (e.g., sulphates, etc.) show good agreement with pollutants from anthropogenic sources, and suggest underestimates of the contribution from natural (e.g., biogenic) sources. As pointed out above, the health impact assessment in GAINS considers exposure to PM2.5 from anthropogenic sources only, so that this deficiency might be of less relevance for the calculation of health effects.

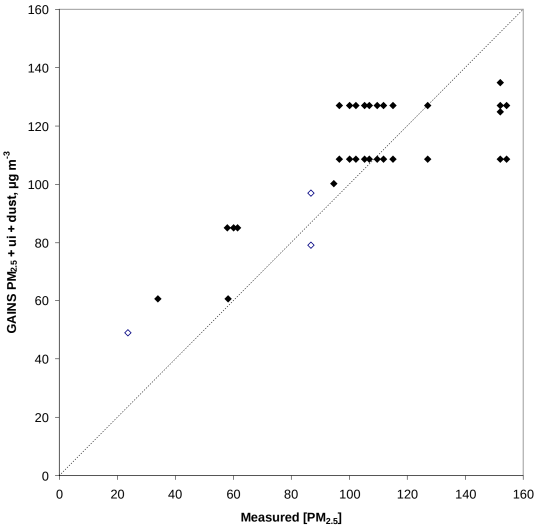

Figure 2.6: Comparison of GAINS estimates of PM2.5 with available PM2.5 measurements in Chinese cities. Open symbols represent rural sites for which no urban increment was applied to the GAINS estimate.

2.2.2 CONCENTRATIONS OF GROUND-LEVEL OZONE

GAINS also estimates concentrations of ground-level ozone (annual mean concentrations are shown in Figure 2.7) and assesses resulting impacts on human health and crops using different ozone exposure metrics. Annual mean concentrations of ozone are computed in a range between 40 to 50 ppb in most parts of China. Higher concentrations are estimated for the western provinces.

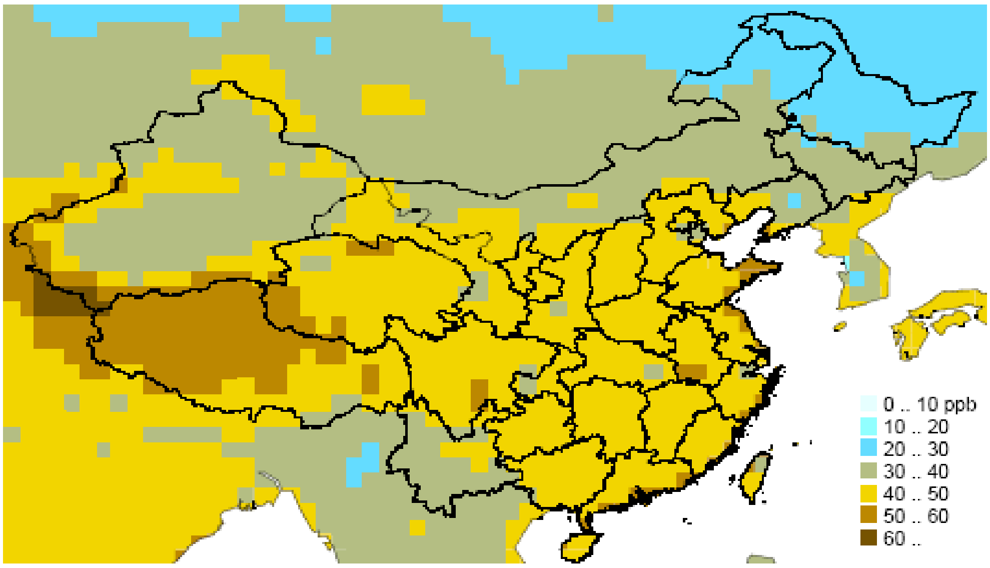

Figure 2.7: Rural annual mean concentrations of ozone, computed for the emissions of 2005. Note that in cities ozone will be lower due to titration with local NO_x emissions.

2.3 Air quality impacts

2.3.1 HEALTH IMPACTS FROM OUTDOOR POLLUTION

For the year 2005, GAINS estimates for the Chinese population a loss in statistical life expectancy attributable to outdoor exposure of PM2.5 of 39 months. Obviously, such a calculation is burdened with significant uncertainties, and sets of alternative assumptions result in a range from 21 to 53 months. Details about the methodology for calculating health impacts are provided in Amann *et al.*, 2008a. It should be noted that the methodology adopted for GAINS associates only exposure to PM2.5 of anthropogenic origin with negative health effects, and does not, therefore, link particles from natural sources (soil dust, sea salt, vegetation, etc.) with reduced life expectancy. More details are provided in Amann *et al.*, 2008b.

Since GAINS computes ambient concentration based on a detailed chemical transport model, it allocate the contributions to ambient PM2.5 concentrations to their different origins, both from natural and anthropogenic sources. It has been pointed out above that combustion of solid fuels in households constitutes in China a major source of PM emissions. Analysis shows that about 20 percent of the health impacts from outdoor exposure to PM2.5 can be linked to emissions from the combustion of solid fuels in households (Figure 2.8), which are responsible, in addition to their outdoor health effects, for serious health impacts through the exposure to indoor pollution.

Table 2.5: Loss in statistical life expectancy in China estimated for 2005 (months)

	Central estimate	Lower estimate	Upper estimate	Central estimate without emissions from solid fuel combustion in households
ANHUI	52.6	27.6	70.8	42.1
BEIJING	57.3	30.0	77.1	40.3
CHONGQING	54.3	28.5	73.1	46.4
FUJIAN	20.3	10.6	27.3	19.1
GANSU	15.4	8.0	20.7	13.5
GUANGDONG	32.7	17.1	44.0	28.8
GUANGXI	33.4	17.5	45.0	29.5
GUIZHOU	33.2	17.4	44.7	29.6
HAINAN	13.7	7.2	18.4	12.7
HEBEI	48.3	25.3	65.0	38.5
HEILONGJIANG	12.7	6.6	17.1	8.2
HENAN	54.5	28.5	73.3	45.9
HUBEI	48.4	25.3	65.1	40.4
HUNAN	43.8	22.9	58.9	38.0
INNER MONGOLIA	8.8	4.6	11.9	7.4
JIANGSU	53.9	28.2	72.6	44.9
JIANGXI	38.0	19.9	51.2	33.5
JILIN	22.2	11.6	29.9	14.2
LIAONING	31.6	16.6	42.6	22.8
NINGXIA	14.2	7.5	19.2	12.1
QINGHAI	13.2	6.9	17.7	9.8
SHAANXI	30.8	16.2	41.5	25.9
SHANDONG	49.0	25.6	65.9	40.1
SHANGHAI	51.9	27.2	69.9	47.4
SHANXI	33.5	17.6	45.2	29.8
SICHUAN	55.5	29.1	74.7	43.4
TIANJIN	50.9	26.7	68.6	40.8
TIBET XIZANG	1.8	1.0	2.5	1.8
XINJIANG	7.6	4.0	10.2	6.0
YUNNAN	17.1	9.0	23.1	15.6
ZHEJIANG	35.7	18.7	48.1	32.4
CHINA	**39.4**	**20.6**	**53.1**	**32.8**

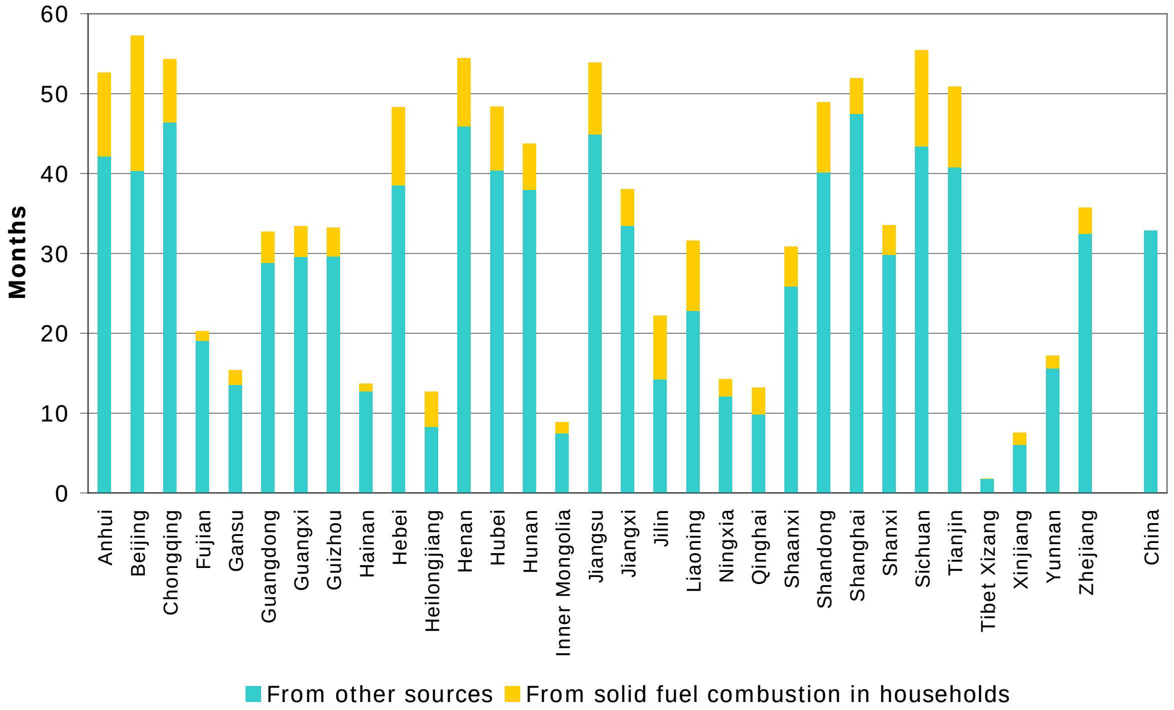

Figure 2.8: Loss in statistical life expectancy that can be attributed to the outdoor exposure to PM2.5 in China in 2005, central estimate

2.3.2 HEALTH IMPACTS FROM INDOOR POLLUTION

The GAINS model estimates health impacts from indoor pollution resulting from solid fuel use in households, following the methodology employed for the Global Burden of Disease project of the World Health Organization (Smith *et al.*, 2004). In line with the WHO methodology, GAINS calculations result in disability adjusted life years as the metric for health impacts. In contrast to outdoor effects, which are quantified only for the population older than 30 years, estimates of health impacts from indoor pollution also relate to children. Estimates for the year 2005 are presented in Table 2.6. It should be noted that comparability with the estimates for outdoor effects needs further work, including harmonization of underlying assumptions.

Table 2.6: Disability adjusted life years (DALY) from indoor pollution, China 2005 (1000 DALYs/year)

		2005
ALRI FROM INDOOR BURNING OF BIOMASS	Children < 5 yrs	1454
COPD FROM INDOOR BURNING OF BIOMASS	Women	1869
LUNG CANCER (FROM EXPOSURE TO COAL SMOKE)	Women	209
COPD FROM INDOOR BURNING OF BIOMASS	Men	1227
LUNG CANCER (FROM EXPOSURE TO COAL SMOKE)	Men	279
TOTAL		**5037**

ALRI: Acute lower respiratory infections

COPD: Chronic obstructive pulmonary disease

2.3.3 CROP LOSSES FROM GROUND-LEVEL OZONE

In addition to health impacts, GAINS estimates for a number of economically important agricultural crops (wheat, corn, rice, soy) potential crop losses that are attributable to ground-level ozone. There are some areas in China for which current ozone levels are likely to cause considerable losses in agricultural productivity. As an example, Figure 2.9 shows the spatial distribution of potential crop losses for wheat, which reaches in some areas of eastern China more than 20 percent.

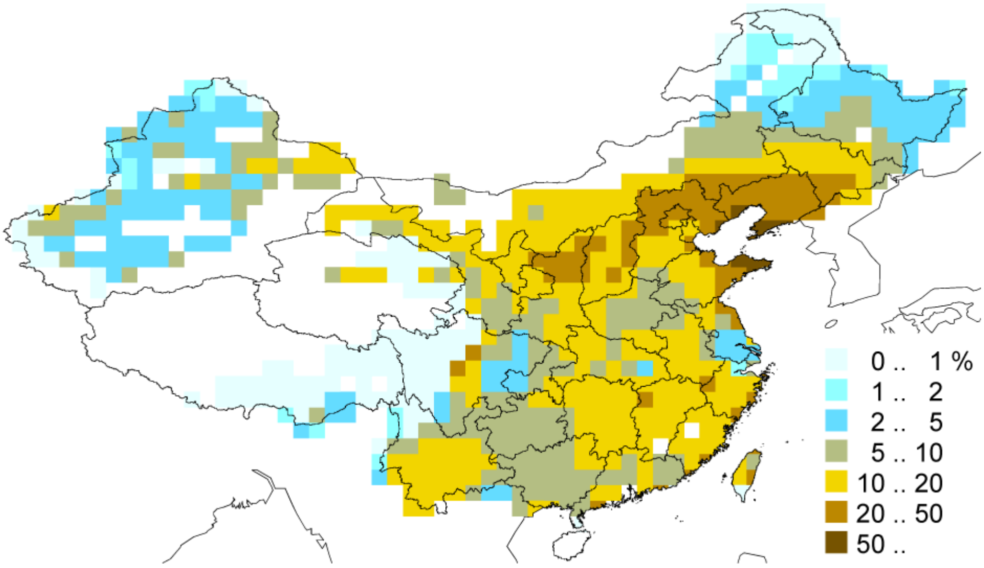

Figure 2.9: Potential losses in wheat yield due to ground-level ozone in 2005, %

3 The baseline projection up to 2030

3.1 Macro-economic development and energy consumption

As a reference for the analysis of alternative policy scenarios, the Chinese Energy Research Institute has developed a baseline projection that reflects current Chinese expectations on (i) population projections of the National Population Development Strategy, (ii) the official Chinese industrial process forecasts, (iii) the 1997-2010 Land Plan Program of the Ministry of Land and Resource (2004), (iv) the national government's development targets for renewable energy sources in the '11th Five Year Plan', and (v) the IPAC-AIM/Local energy model.

The baseline scenario extrapolates business as usual assuming that existing policies on energy and environment will be continued and implemented. Technology progress keeps at a moderate level. International trading will increase and China's economy will be integrated further into the global economy. Therefore, China could rely on international markets and energy imports to meet part of its energy supply needs.

Overall, the baseline scenario projects an increase of total GDP (in constant 2000 Yuans) by a factor of 10 between 2000 and 2030 (i.e., by eight percent per year), while total population would increase by 15 percent. This implies a growth in per-capita GDP from €1,275 in 2005 to €7,000, i.e., by a factor of 5.5 if measured in Market Exchange rates, or from €3,000 to €9,100, i.e., by a factor of three in terms of Purchasing Power Parity.

Such an economic growth will put heavy demand on the supply of energy. Under business-as-usual conditions, consumption of total primary energy is estimated to increase by a factor of 3.2 between 2005 and 2030, indicating a clear decoupling between economic growth and energy consumption as a consequence of the ongoing structural transformations in the Chinese economy.

As the growth in the transport sector will further deteriorate China's oil import dependency, maximum utilization of indigenously available energy resources is seen as an important measure to safeguard energy security. Thus consumption of coal is projected to grow by 80 percent, mainly to fuel power generation. Oil demand is expected to grow by 160 percent, and renewable energy by a factor of four (Table 3.1).

Table 3.1: Baseline projection of fuel consumption for China (PJ/yr)

	1990	2000	2005	2010	2020	2030
COAL	20694	29946	51315	67595	74336	91976
OIL	5192	7700	11174	14068	22060	29350
GAS	1004	1236	1836	2429	3734	5626
RENEWABLES	456	1034	1812	2433	4391	7926
NUCLEAR	0	0	927	1853	7219	12157
BIOMASS	8395	9200	8750	8721	7916	8013
TOTAL	**35741**	**49116**	**75814**	**97099**	**119656**	**155048**

One of the factors that contribute major uncertainties to the influence on the long-term development - and which is also most difficult to accurately predict - concerns the future rate of economic growth. With an assumed annual growth rate of eight percent, this baseline represents a medium-range development path among the alternatives that are currently discussed in China. However, some energy projections that have been developed by international institutions assume somewhat lower growth. For instance, the World Energy Outlook 2007 of the International Energy Agency assumes an annual GDP growth of six percent up to 2030 (IEA, 2007), and global energy projections that have been developed for the Intergovernmental Panel on Climate Change (Nakicenovic *et al.*, 2000 and updates thereof) employ growth rates between 6.8 and 7.6 percent/year (in market exchange rates).

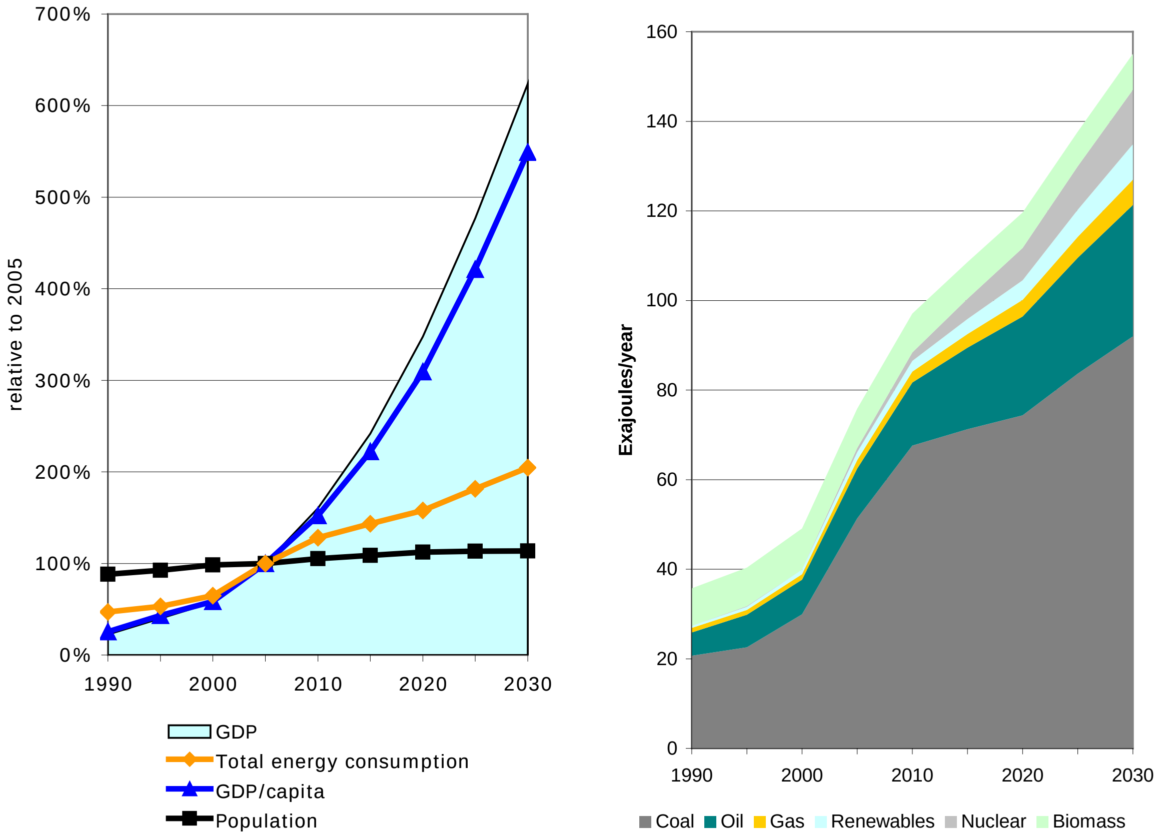

Figure 3.1: Assumptions on macro-economic development and energy consumption of the baseline projection. Left panel: Macro-economic indicators, relative to the year 2005. Right panel: Primary energy consumption (in Exajoules/year)

The projections of future agricultural activity have been derived from an agricultural production model formulated for the CHINAGRO and CATSEI projects (Fischer *et al.*, 2006; Huang *et al.*, 2003). The dynamic livestock and crop production model integrates demographic, economic, agricultural and environmental modelling components and assesses agricultural production from a demand side. It combines spatially explicit data from census as well as soil and climatic properties and addresses national, sub-national, and regional interactions of agricultural activities, production, processing, and consumers. Projections include, on the scale of Chinese counties, numbers of each type of animals, milk production, and area of cultivated land, grassland and histosols, N fertilizer application, N input into agriculture from crop residues. The animal production is divided into grazing, industrial, special and traditional systems. Additional assumptions on the shares of liquid vs. solid systems had to be taken for each of the systems and animal types to match results with data useable in GAINS. The model has been applied to different economic growth scenarios in China, with different regional consequences in terms of population growth and urbanization.

The resulting growth rates differ by animal category, fertilizer type as well as by province. Total cattle numbers are expected not to change significantly until 2030, while the number of pigs and poultry are projected to increase by 30 and 60 percent, respectively. Fertilizer consumption is expected to grow by 20 percent (Figure 3.2).

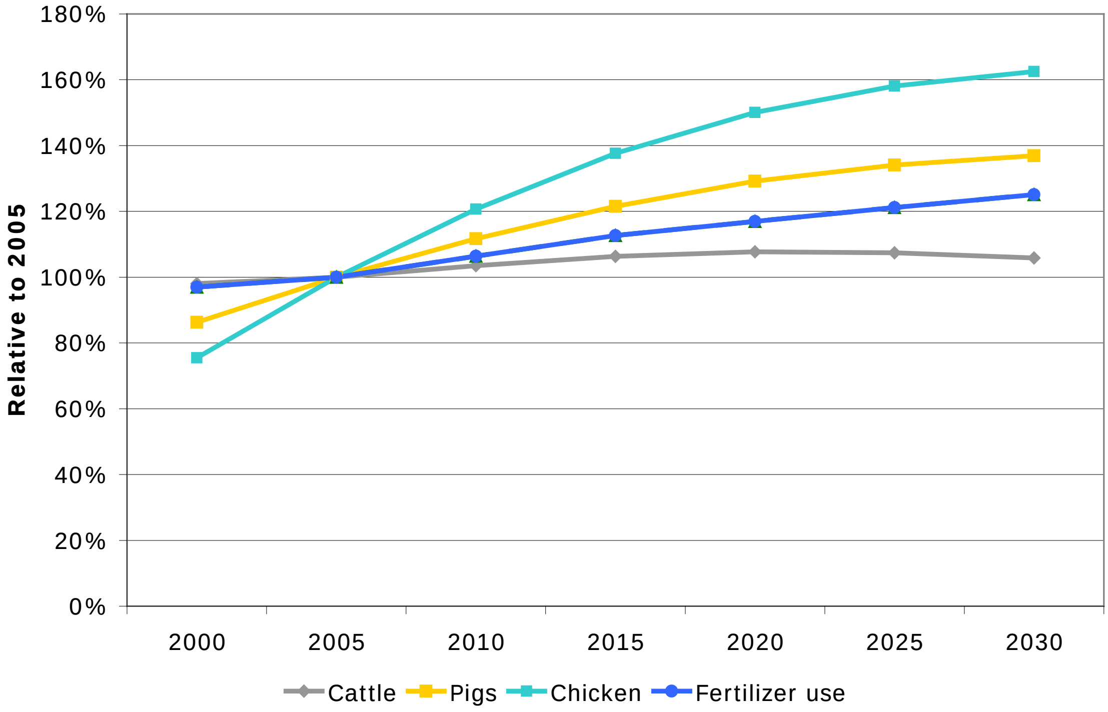

Figure 3.2: Projections of agricultural activities for China

3.2 Baseline projections for air pollution emissions

It is obvious that, as a consequence of sharply increasing fuel consumption in China, emissions of air pollutants and greenhouse gases will grow accordingly unless stricter measures for controlling emissions will be taken in the future. The exact level of future emissions will therefore be critically determined by the extent to which emissions will be controlled through targeted policy interventions.

To assess cost-effective policy interventions that maintain acceptable levels of air quality, a baseline projection is developed as a reference case. This baseline projection explores the likely development of air pollution and greenhouse gas emissions as well as their local impacts under the assumptions that (i) currently existing policies and regulations on air pollution control measures were fully implemented as foreseen, and (ii) that no additional measures were adopted. The baseline projection explicitly considers the impacts of the implementation of emission control measures for stationary and mobile sources as summarized in Table 3.2. It is assumed that the implementation of these measures will follow current practices.

Table 3.2: Emission control measures assumed in the baseline

Stationary sources	Mobile sources
• Large combustion plants: o Electrostatic precipitators (ESP) at large combustion plants to control emissions of particulate matter, with high removal efficiency (99%) for all plants built after 2005 o Less efficient ESP for large plants built before 2005 o Increasing penetration of flue gas desulphurization (FGD) after 2005 in new and existing plants • Small to medium combustion plants in the power sector and industry: o Cyclones or less efficient ESP for plants built before 2005 o Significant share of plants using low sulphur coal (0.6% S) already in 2005 o Increasing penetration of in-furnace sulphur controls (limestone injection) and to some extent also FGD after 2005 in new plants	• Two-wheelers: o Euro-II (Stage-II) controls after 2003 o Euro-III (Stage-III) controls after 2006 • Light duty and heavy duty vehicles(*): o Euro-1/I after 2000 o Euro-2/II after 2004 o Euro-3/III after 2006 o Euro-4/IV after 2010 o Euro V after 2012 • Off-road machinery (agricultural and construction): o Euro-1/I after 2007 o Euro-2/II after 2009 • Low sulphur gasoline (10 ppm) from 2010 • Low sulphur diesel (10 ppm) from 2010

*) In larger cities (e.g., Beijing, Shanghai) implementation of some measures occurs up to two years earlier

With full implementation of the legislation on air pollution emissions as outlined in Table 3.2, emissions of SO_2 should stabilize approximately at the 2005 levels up to 2030 (Figure 3.3). Phase-out of solid fuels from small sources in households will gradually reduce primary emissions of PM2.5, so that they should be 10 percent lower in 2030. In contrast, current legislation will not be sufficient to prevent further increases in NO_x. While the introduction of stringent legislation on mobile sources will compensate for further growth in transport volumes, emissions from large stationary sources in the power sector and in industry are expected to increase significantly. In total, it is expected that Chinese NO_x emissions would be 50 percent higher in 2030 than today. Significant growth in mineral N-fertilizer application and livestock and no change in agricultural practice will result in an increase of NH_3 emissions by 30 percent For VOC, declining emissions from the combustion of solid fuels in households are likely to be compensated by higher emissions from solvents and industrial activities.

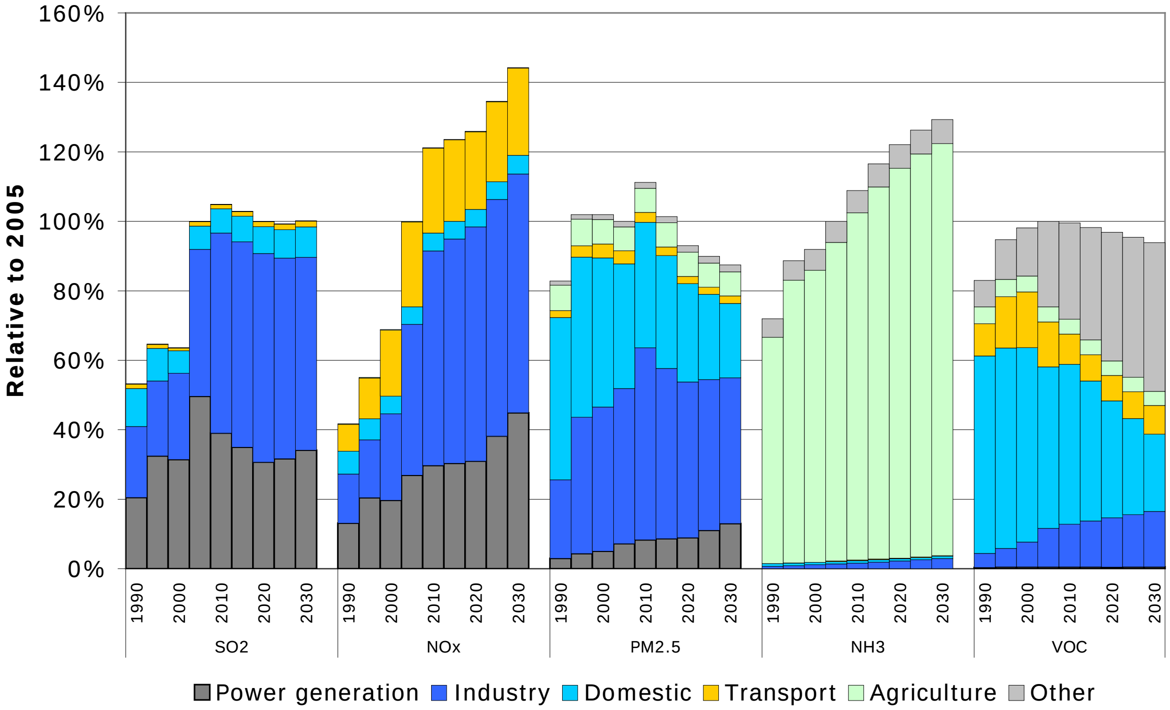

Figure 3.3: Baseline projection of air pollutant emissions in China 1990-2030 by sector. Emissions are scaled to the level of total emissions in 2005.

In contrast to air pollutants, the lack of effective mitigation measures will lead to a strong increase in greenhouse gas emissions (Figure 3.4). The projected increase in economic activities would multiply CO_2 emissions by more than a factor of four. CH_4 and N_2O emissions, which originate mainly from agricultural activities, are expected to increase by 50 percent. As a consequence, total greenhouse gas emissions would triple.

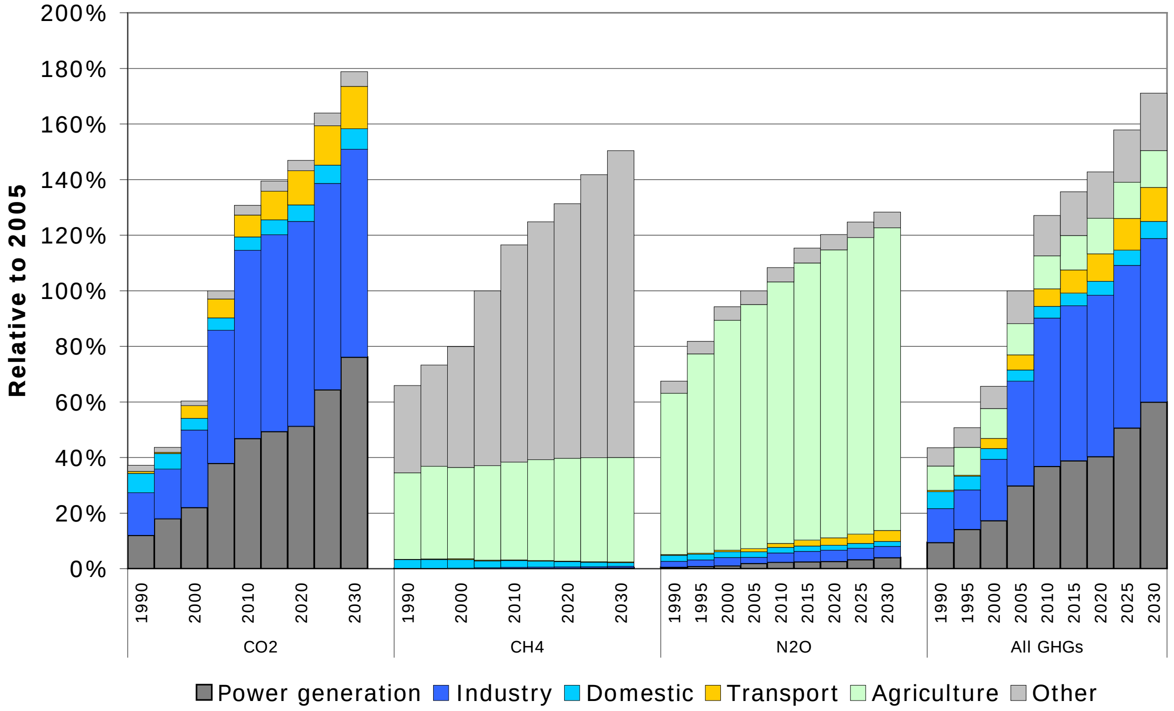

Figure 3.4: Baseline projection of greenhouse gas emissions in China 1990-2030 by sector. Emissions are scaled to the level of total emissions in 2005.

It is important to realize that the baseline emission projection assumes as an integral part the implementation of dedicated emission control measures as listed in Table 3.2. Thus, the baseline projection takes into consideration that significant economic resources will be spent for air pollution control. For 2005, the costs of implemented pollution control measures are estimated at €14.6 billion or 0.37 percent of the GDP. About half of the costs emerged for control of PM emissions from industrial facilities, one quarter for PM and SO_2 controls in the power sector and 17 percent for controlling emissions from road transport. In 2030, implementation of current emission control laws would involve costs of €90 billion, or 0.68 percent of GDP (expressed in PPP).

Table 3.3: Air pollution control costs in 2005 and 2030 in China

	2005		2030 baseline	
	billion €/yr	% of GDP	billion €/yr	% of GDP
POWER GENERATION	4.0	0.10%	15.7	0.12%
INDUSTRY	7.6	0.19%	21.9	0.16%
DOMESTIC	0.4	0.01%	0.6	0.00%
TRANSPORT	2.5	0.06%	52.2	0.39%
AGRICULTURE	0.0	0.00%	0.0	0.00%
TOTAL	**14.6**	**0.37%**	**90.4**	**0.68%**
GDP (PPP)	3947		13342	

3.3 Baseline projections of air quality and health impacts

Despite current efforts to control air pollution in China, the path in emissions as portrayed for the baseline projection would not result in major air quality improvements in China in the coming decades. Most relevant for health impacts, present annual mean concentrations of fine particles (PM2.5) already exceed the guideline value of the World Health Organization of 10 µg/m^3 virtually everywhere throughout the eastern part of China, and typically reach more than 100 µg/m^3 in the industrial centres (Figure 3.5).

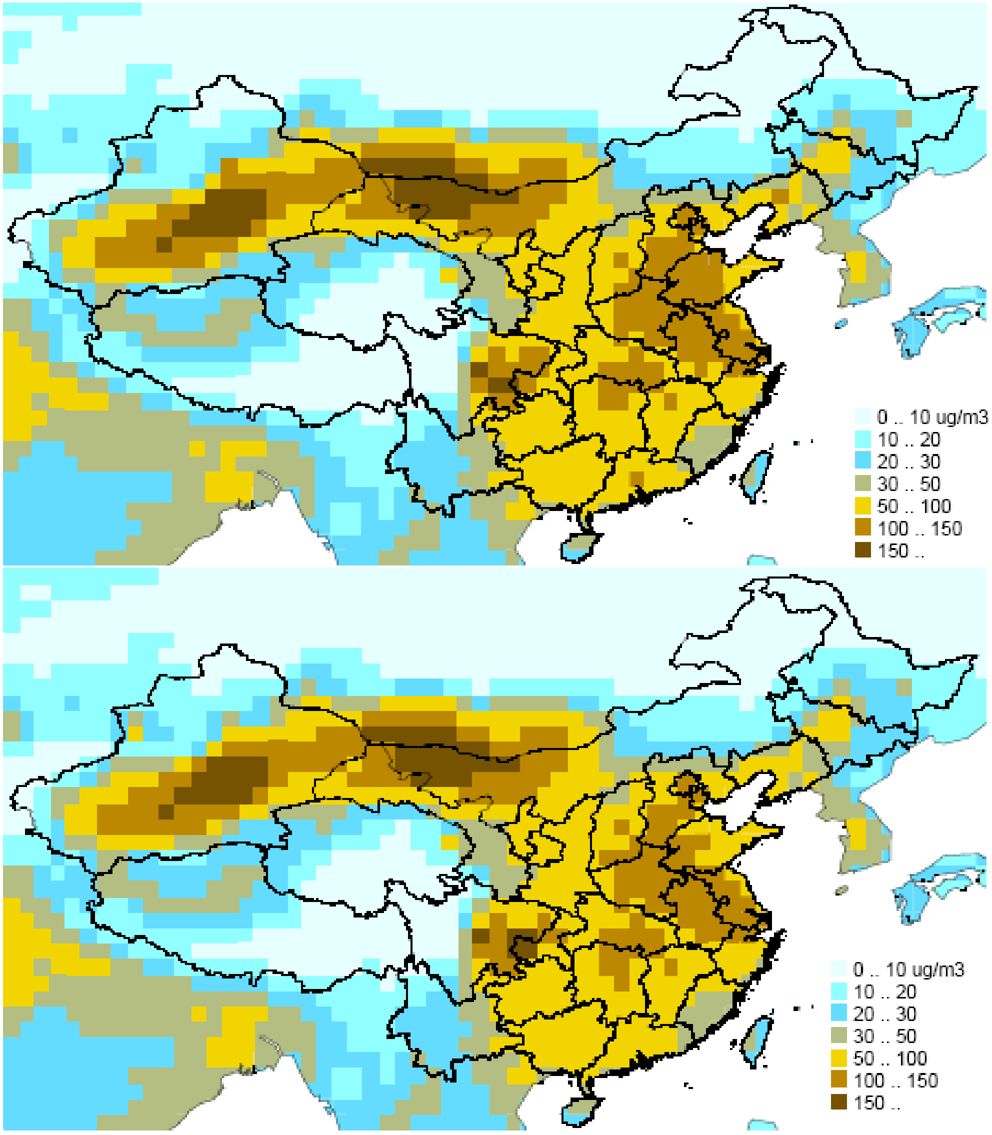

Figure 3.5: Computed annual mean concentrations of PM2.5 that are representative for rural and urban background sites, in 2005 (upper panel) and for the baseline emission scenario in 2030 (lower panel). This calculation includes particles from natural sources (e.g., soil dust).

This stagnation in ambient PM2.5 concentrations will not allow significant improvements in health impacts from outdoor pollution. For all of China, loss in statistical life expectancy that can be attributed to the exposure to PM2.5 from anthropogenic sources will remain in 2030 at 39 (21-53) months. Spatial variations in ambient PM2.5 concentrations lead to significant differences in health impacts across China; by in 2030, life shortening in Chongqing would amount to more than 60 (31-80) months, in contrast to Tibet for which 2 (1-3) months are calculated (Figure 3.6).

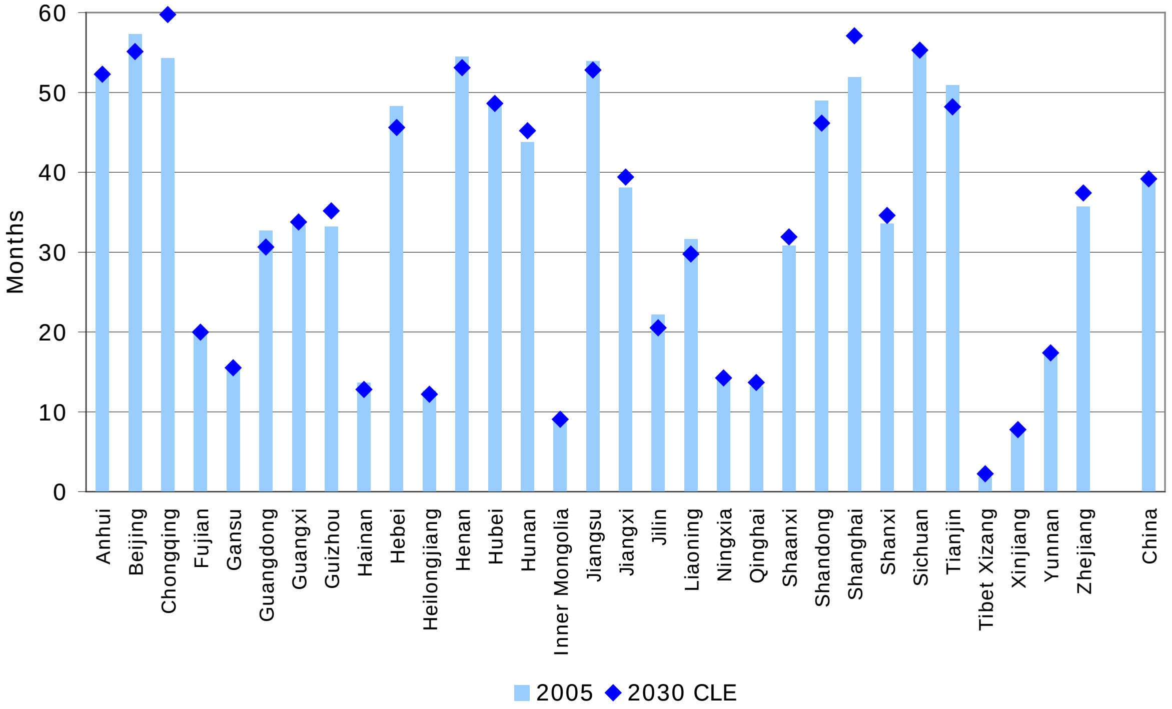

Figure 3.6: Loss in statistical life expectancy attributable to the outdoor exposure of fine particulate matter computed for 2005 and the 2030 baseline projection (central estimate)

While for an individual Chinese citizen loss in statistical life expectancy would remain at current levels in the coming two decades, total health impacts from outdoor pollution would increase. This is caused by the general growth in the Chinese population and enhanced by the ongoing aging process of the society, which will increase the number of people older than 30 years for which health impacts are estimated, from 687 million in 2005 to 925 million in 2030. Together, these factors will increase the total number of life years that are lost due to outdoor pollution from 56 to 76 million years lost/year.

In contrast to outdoor sources, health impacts from indoor pollution are expected to decline by about 40 percent despite growing population (Table 3.4). This is a direct consequence of the phase-out of solid fuel combustion in households that is assumed in the baseline energy projection. Although the reduced consumption of solid fuels in households will cause less health impacts from indoor exposure, it will cause higher health damage through outdoor exposure to PM2.5 as a consequence of the enlarged number of exposed people caused by the growth and ageing of Chinese population.

Table 3.4: Disability adjusted life years (DALY) attributable to indoor pollution from the combustion of solid fuels in the domestic sector in China for 2005 and the baseline projection in 2030 (1000 DALYs/year)

		2005	2030
CHILDREN	ALRI	1454	641
WOMEN	COPD	1869	825
WOMEN	Lung cancer	209	313
MEN	COPD	1227	541
MEN	Lung cancer	279	419
TOTAL		**5037**	**2740**

In contrast to air pollutant emissions, for which emission control measures are currently being implemented, increased energy consumption associated with the rapid economic development will cause a substantial growth in greenhouse gas emissions. While the assessment of resulting climate impacts is beyond the scope of the GAINS model, the magnitude of the anticipated growth will certainly be relevant even at the global scale. Although Chinese per-capita emissions will remain lower than those of other countries in the world, the increase in total emissions would make China clearly the country with the highest GHG emissions (Figure 3.7).

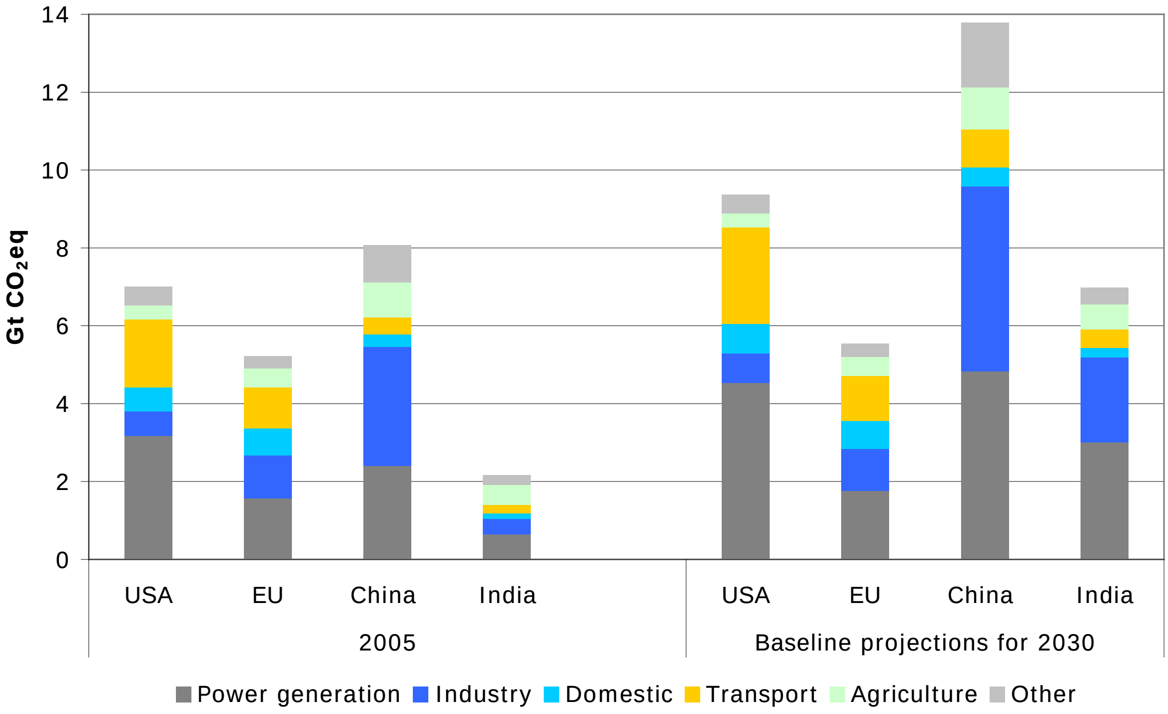

Figure 3.7: Greenhouse gas emissions of the USA, EU, China and India, 2005 and baseline projections for 2030, by sector

4 Alternative policy scenarios

As demonstrated in the preceding section, current emission control legislation will not be sufficient to substantially improve air quality in China. It will be shown in this section that application of a wide range of available measures that are not yet required by Chinese law can reduce emissions and thereby lead to better air quality. Thus, there is a wide field of possible policy interventions to achieve more sustainable living conditions in terms of air quality. However, there are significant differences in the effectiveness and costs of the available measures, so that ill-designed pollution control strategies might place unnecessary burdens on the economy.

This section explores the cost-effectiveness of alternative emission control strategies. It should be emphasized that the choice of the appropriate balance between the environmental ambition level and the willingness of a society to spend economic resources for achieving such levels is a genuinely political decision and certainly beyond the scope of a scientific analysis. Therefore, the scenarios presented in this paper illustrate basic features of different conceptual approaches towards improved air quality, and the power of an integrated perspective on pollution control that could substantially reduce the expenditure of economic resources compared to conventional approaches.

4.1 Uniform application of advanced emission control technologies for large sources

As shown before, with the presently expected economic growth the current implementation schedule of further emission control measures will not be sufficient for reducing air pollution in China.

Industrialized countries in the West have demonstrated that the growth in air pollution emission can be successfully decoupled from economic growth through the application of advanced end-of-pipe emission control technologies. Such measures include, inter alia, flue gas desulfurization to reduce SO_2 emissions, selective catalytic reduction to reduce NO_x emissions from large boilers, high-efficiency devices to control particle emissions from boilers and industrial processes, and advanced control technologies for light and heavy duty vehicles. Such control measures are widely applied in industrialized countries, and often requested from all installations in order to avoid distortion of economic competitiveness across different companies.

A scenario is analyzed which assumes for 2030 the full implementation of the above mentioned measures to all relevant emission sources in China. Thereby, the scenario explores a situation where advanced end-of-pipe technologies for controlling SO_2, NO_x and PM emissions for large stationary sources in the power sector and industry) and for light and heavy duty vehicles are applied in all of China. However, no further controls beyond current legislation are assumed for VOC emissions and for the domestic sector. Such a widespread and undiscriminating application of advanced emission control technologies could substantially reduce future emissions in China below the baseline case (Table 4.1). In particular, SO_2 emissions could be cut by more than half compared to 2005; NO_x emissions could be one third lower than in 2005, and PM2.5 emissions would be cut by two thirds.

However, the across-the-board application of advanced technologies comes at certain costs. By 2030, air pollution control costs would increase to €174 billion/yr, or 1.3 percent of the GDP. While this is substantially higher than the €90 billion/yr (0.68% of GDP) of the current legislation case, it should be remembered that the underlying economic projection for 2030 assumes GDP to grow by 450 percent (in Market Exchange Rates) or by 200 percent (based on Purchasing Power Parity).

Table 4.1: Emissions (Mt) and control costs (billion €/yr) of the Advanced Control Technology (ACT) scenario in 2030 compared to the Current Legislation (CLE) scenario and the estimates for the year 2005

	SO_2			NO_x			PM2.5			Costs		
	2005	2030		2005	2030		2005	2030		2005	2030	
		CLE	ACT		CLE	ACT		CLE	ACT		CLE	ACT
POWER	15.6	10.8	2.9	4.6	7.6	2.3	0.9	1.7	0.3	4.0	15.7	26.5
INDUSTRY	13.3	17.5	9.3	7.3	11.6	5.2	5.7	5.3	1.0	7.6	21.9	52.4
DOMESTIC	2.1	2.8	2.8	0.9	0.9	0.9	4.6	2.7	2.7	0.4	0.6	0.9
TRANSPORT	0.4	0.5	0.0	4.1	4.3	2.3	0.5	0.3	0.2	2.5	52.2	90.7
AGRICULT.	0.0	0.0	0.0	0.0	0.0	0.0	0.9	0.9	0.2	0.0	0.0	0.3
OTHER	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.3	0.2	0.0	0.0	3.1
TOTAL	**31.5**	**31.6**	**15.0**	**16.9**	**24.4**	**10.7**	**12.7**	**11.1**	**4.6**	**14.6**	**90.4**	**173.8**
% OF GDP										**0.37%**	**0.68%**	**1.30%**

While such a pollution control strategy would involve considerable economic resources, it also results in significant health and environmental benefits. Population-weighted ambient concentrations of PM2.5 would decline from 80 µg/m^3 in the baseline case to 45 µg/m^3 (Figure 4.1). Thereby, by 2030 cleaner air would reduce the loss in statistical life expectancy attributable to fine particles from 39 months in the current legislation case to 22 (12-30) months. Since the strategy focuses on controls of large emission sources, however, health impacts from indoor pollution would not be affected. (Table 4.4).

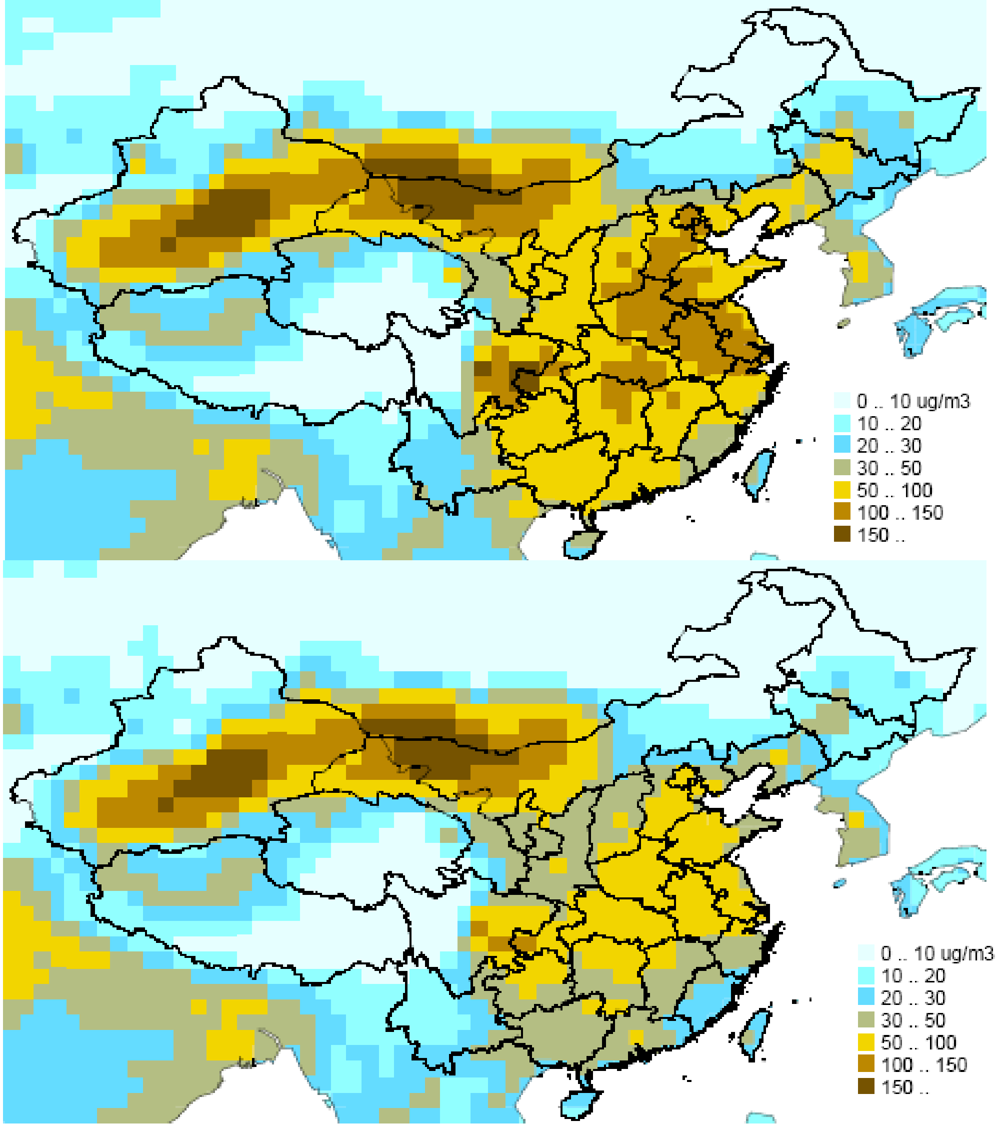

Figure 4.1: Ambient concentrations of PM2.5 computed for the Current Legislation (CLE) case in 2030 (top panel) and the Advanced Control Technology (ACT) case (bottom panel), including dust from natural sources

The reductions in precursor emissions would also lead to lower concentrations of ground-level ozone, and thereby to less health impacts and crop damage. The changes in emissions (especially of NO_x) would lead to an increase in the cases of premature deaths that are attributable to the exposure to ground-level ozone by more than 10 percent between 2005 and 2030. In contrast, application of advanced control technologies would reduce health impacts from ozone by 20 percent compared to 2005, or 28 percent if compared to the baseline projection (Table 4.2).

Table 4.2: Cases of premature deaths that are attributable to the exposure to ground-level ozone, for 2005, the Baseline scenario in 2030 and the ACT scenario

	2005	Baseline scenario 2030	Advanced control technology, 2030
ANHUI	2410	2661	2075
BEIJING	457	494	396
CHONGQING	759	859	520
FUJIAN	1299	1515	1036
GANSU	799	965	596
GUANGDONG	2335	2666	1874
GUANGXI	1269	1464	882
GUIZHOU	1063	1261	688
HAINAN	279	311	222
HEBEI	3069	3282	2583
HEILONGJIANG	158	195	126
HENAN	3626	3885	2863
HUBEI	2201	2470	1657
HUNAN	2604	2926	1931
INNER MONGOLIA	630	747	515
JIANGSU	2962	3327	2695
JIANGXI	1577	1841	1231
JILIN	497	559	425
LIAONING	1706	1844	1495
NINGXIA	142	172	110
QINGHAI	162	196	129
SHAANXI	1378	1621	1032
SHANDONG	4277	4536	3655
SHANGHAI	408	501	372
SHANXI	1446	1615	1180
SICHUAN	2810	3044	1975
TIANJIN	286	308	236
TIBET XIZANG	121	127	120
XINJIANG	342	393	299
YUNNAN	900	1011	705
ZHEJIANG	1529	1748	1359
TOTAL	**43497**	**48539**	**34980**

In addition, lower emissions also reduce concentrations of ground-level ozone and thereby impacts on human health and vegetation. As an example, Figure 4.2 compares potential crop losses for wheat, which would be halved by the measures of the ACT scenario.

Table 4.3: Potential losses of agricultural production due to ground-level ozone, for the year 2005 and the Current Legislation (CLE) and Advanced Control Technology (ACT) scenarios in 2030, (in kilotons)

	Rice			Wheat			Soybean		
	2005	CLE	ACT	2005	CLE	ACT	2005	CLE	ACT
ANHUI	498	591	427	782	863	669	105	119	83
BEIJING	3	3	2	235	253	195	2	2	1
CHONGQING	79	95	49	76	93	48	8	9	5
FUJIAN	129	166	85	17	20	14	...	...	...
GANSU	1	1	1	309	382	227	4	6	2
GUANGDONG	235	287	163	4	5	4	...	...	...
GUANGXI	136	173	78	5	5	3	1	2	0
GUIZHOU	54	77	24	84	102	51	2	4	1
HAINAN	14	16	10	0	0	0	...	...	...
HEBEI	29	32	23	2428	2583	1959	78	85	62
HEILONGJIANG	7	10	5	13	17	9	26	37	18
HENAN	120	138	87	2042	2235	1585	157	175	116
HUBEI	565	674	388	330	362	241	63	79	41
HUNAN	796	959	549	41	45	28	5	7	3
I. MONGOLIA	1	1	1	215	255	175	2	2	1
JIANGSU	667	775	622	992	1120	921	100	116	89
JIANGXI	560	720	393	18	20	14	3	5	2
JILIN	5	7	4	23	27	19	45	56	35
LIAONING	13	15	12	192	206	165	38	43	32
NINGXIA	14	18	9	103	127	80	...	...	...
QINGHAI	...	...	...	31	41	20	...	...	...
SHAANXI	13	17	8	522	620	368	33	43	21
SHANDONG	9	9	7	4654	4998	4033	144	158	118
SHANGHAI	11	14	10	8	9	7	3	4	3
SHANXI	0	0	0	419	470	320	9	11	6
SICHUAN	515	584	327	383	420	250	39	45	25
TIANJIN	3	3	2	152	162	122	8	9	6
TIBET-X.	...	...	...	0	0	0	...	...	...
XINJIANG	0	0	0	169	191	149	...	...	...
YUNNAN	13	17	8	219	229	199	1	2	0
ZHEJIANG	329	396	286	66	77	59	7	8	6
TOTAL	**4817**	**5800**	**3577**	**14530**	**15935**	**11935**	**883**	**1022**	**678**

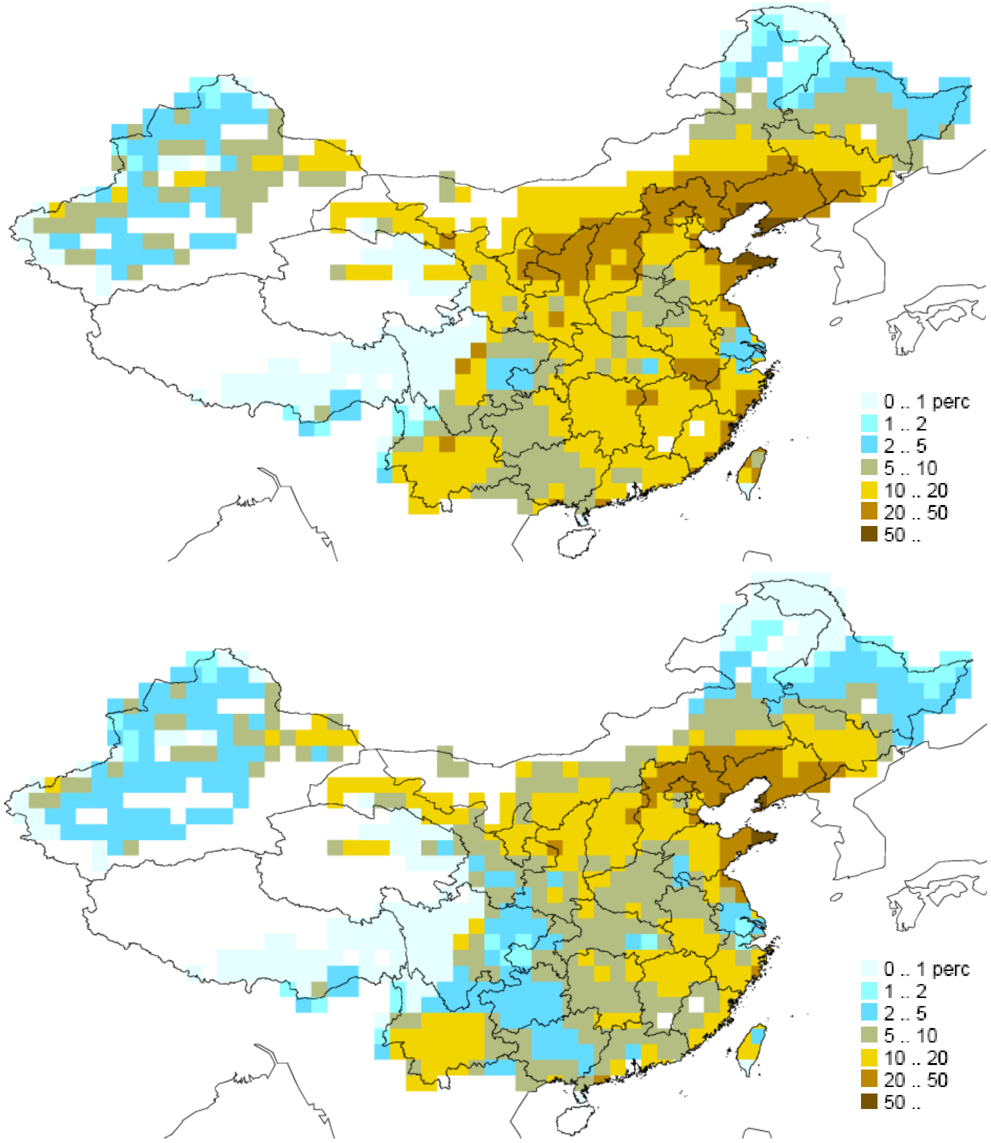

Figure 4.2: Potential crop losses for wheat computed for the Current Legislation (CLE) case in 2030 (top panel) and the Advanced Control Technology (ACT) case (bottom panel)

In summary, full application of advanced emission control measures to large sources could substantially reduce emissions in the future, which would lead to significantly improved air quality and lower air pollution damage to human health, agricultural crops and the natural environment (Table 4.4).

Table 4.4: Comparison of impact indicators for the Current Legislation (CLE) and Advanced Control Technology (ACT) scenarios in 2030, compared to the estimates for 2005

		2005	2030 CLE	2030 ACT
LOSS IN STATISTICAL LIFE EXPECTANCY	Months	39.4	39.2	22.4
YEARS OF LIFE LOST (YOLLS) FROM OUTDOOR POLLUTION	Million years/yr	56.4	75.6	43.1
DISABILITY ADJUSTED LIFE YEARS FROM INDOOR POLLUTION	Million years/yr	5.0	2.7	2.7
CASES OF PREMATURE DEATHS FROM GROUND-LEVEL OZONE	1000 cases/yr	45.5	48.5	35.0
POTENTIAL CROP LOSS FOR RICE	Million tons/yr	4.8	5.8	3.6
POTENTIAL CROP LOSS FOR WHEAT	Million tons/yr	14.5	15.9	11.9
POTENTIAL CROP LOSS FOR SOYBEAN	Million tons/yr	0.9	1.0	0.7

4.2 Cost-effective allocation of end-of-pipe air pollution controls

As shown above, full application of advanced emission control technology that is currently available on the world market can substantially reduce air pollution impacts in China. However, while such a uniform across-the-board strategy would cut, for instance, the loss in statistical life expectancy by 43 percent compared to the baseline case, its implementation would require substantial costs and would increase the share of air pollution control costs in total GDP from 0.37 percent in 2005 to 1.3 percent in 2030. Although this fraction is small in comparison to the projected increase in China's total GDP (+240 percent in PPP between 2005 and 2030), it is higher than what industrialized countries typically spend on air pollution controls.

Numerous policy applications of the RAINS model in Europe have demonstrated that a uniform across-the-board application of advanced emission control measures is usually not a cost-effective way of improving air quality, and that a carefully selected portfolio of measures can achieve the same health and environmental benefits at much lower costs. The GAINS optimization offers a practical tool for a systematic search for a balance of measures across economic sectors and locations that attain exogenously specified environmental targets at least cost.

To explore the potential cost savings from such an approach for China, an alternative emission control scenario has been developed that identifies the cost-effective portfolio of measures that achieves the same health benefits as would result from the across-the-board application of advanced control technologies (i.e., the ACT case as described above). This scenario assumes the same levels of economic activities (i.e., energy consumption, traffic volumes, industrial production, and agricultural activities) as the baseline projection and explores alternative allocations of air pollution emission control measures that achieve the same number of life years lost from PM2.5 as computed for the ACT scenario at lower overall costs. The calculation assumes that measures that are laid down in current Chinese air pollution legislation will be maintained, so that only additional measures that are currently not legally required are considered.

Table 4.5: Emissions in 2030, for the Current Legislation (CLE) case, the scenario with across-the-board application of advanced control technologies (ACT) and the cost-effective allocation determined with the GAINS model (OPT), kilotons

	SO_2			NO_x			PM2.5		
	CLE	ACT	OPT	CLE	ACT	OPT	CLE	ACT	OPT
POWER GENERATION	10758	2933	3265	7592	2342	4646	1650	276	505
INDUSTRY	17499	9259	11648	11645	5232	6189	5340	993	1428
DOMESTIC	2769	2769	1814	905	888	905	2728	2728	1409
TRANSPORT	529	18	529	4251	2252	4251	279	176	279
AGRICULTURE	26	0	0	24	0	0	878	150	153
OTHER	0	0	0	0	0	0	258	248	247
TOTAL	**31581**	**14978**	**17256**	**24417**	**10714**	**15990**	**11133**	**4571**	**4020**

To increase the cost-effectiveness of the control strategy, the allocation of emission control measures across pollutants, economic sectors and provinces is adjusted. In terms of pollutants, the cost minimizing approach reduces less SO_2 and NO_x emissions compared to the uniform ACT case, but puts higher emphasis on the control of PM emissions (Table 4.5).

Cost savings can also be accrued by emphasizing measures at sources that make the largest contribution to population exposure, and relieving the pressure on other sources that contribute less. There is a large cost saving potential by a geographical reallocation of further control measures, to reflect differences in population densities across China and regional differences in the control potentials and costs for different pollutants. Table 4.6 compares the cost-effective allocation of measures for SO_2, NO_x and PM emissions across provinces with the distribution resulting from an across-the-board application of advanced emission control technologies. Differences are represented in graphical form in Figure 4.3 to Figure 4.5.

Table 4.6: Air pollution emissions by province for 2005 and 2030, for the Current legislation (CLE) baseline projection, the case with across-the-board application of advanced control technologies for large sources (ACT) and the cost-effective allocation determined with the GAINS model (OPT), in kilotons

	SO_2				NO_x				PM2.5			
	2005	CLE	ACT	OPT	2005	CLE	ACT	OPT	2005	CLE	ACT	OPT
ANHUI	1143	1095	556	607	753	1064	459	534	614	498	263	162
BEIJING	450	394	248	314	285	323	152	238	115	111	67	35
CHONGQING	928	1474	973	578	308	508	220	275	217	191	79	61
FUJIAN	458	409	176	243	323	410	181	298	175	155	52	61
GANSU	371	309	141	205	279	347	158	195	214	168	74	76
GUANGDONG	1706	1431	441	730	1022	1280	543	978	638	486	189	195
GUANGXI	737	877	422	370	312	428	193	312	397	281	139	165
GUIZHOU	758	881	514	340	285	396	172	259	234	215	105	93
HAINAN	62	42	19	29	64	70	41	56	107	58	46	29
HEBEI	2211	2108	1059	1279	1170	1613	728	1258	941	827	315	217
HEILONGJIANG	460	538	213	509	555	886	364	814	404	339	185	229
HENAN	1638	1504	601	696	876	1182	488	553	815	713	224	159
HONGKONG	21	16	10	12	213	205	111	201	17	15	10	14
HUBEI	1288	1386	705	666	688	1000	435	503	597	472	213	152
HUNAN	745	693	336	389	425	501	235	261	452	391	177	174
I. MONGOLIA	518	533	246	397	375	645	264	568	355	303	152	96
JIANGSU	2179	1844	768	1048	1220	1798	731	817	1007	881	323	214
JIANGXI	536	493	222	293	316	410	184	198	329	294	122	119
JILIN	1830	1695	869	1291	943	1395	630	1224	574	523	238	146
LIAONING	1221	1302	596	845	559	1007	388	441	321	346	120	216
NINGXIA	316	296	108	131	115	212	76	79	76	86	27	27
QINGHAI	74	103	43	61	71	120	48	86	53	64	19	23
SHAANXI	912	954	427	440	337	510	206	231	270	281	113	77
SHANDONG	1337	1520	625	814	815	1362	658	1362	212	284	97	92
SHANGHAI	2791	2506	993	1339	1393	2026	908	971	1137	917	332	229
SHANXI	1927	1839	952	1016	709	1087	445	501	470	499	123	104
SICHUAN	1773	2019	1284	806	566	726	357	415	854	571	337	225
TIANJIN	537	620	315	420	568	873	481	763	120	123	57	42
TIBET XIZANG	4	39	10	39	9	75	24	73	14	28	11	28
XINJIANG	397	463	205	271	240	364	149	291	157	144	61	94
YUNNAN	447	465	216	278	300	399	181	345	319	262	109	139
ZHEJIANG	1752	1731	687	802	831	1194	502	890	524	607	193	327
TOTAL	**31528**	**31581**	**14978**	**17256**	**16926**	**24417**	**10714**	**15990**	**12725**	**11133**	**4571**	**4020**

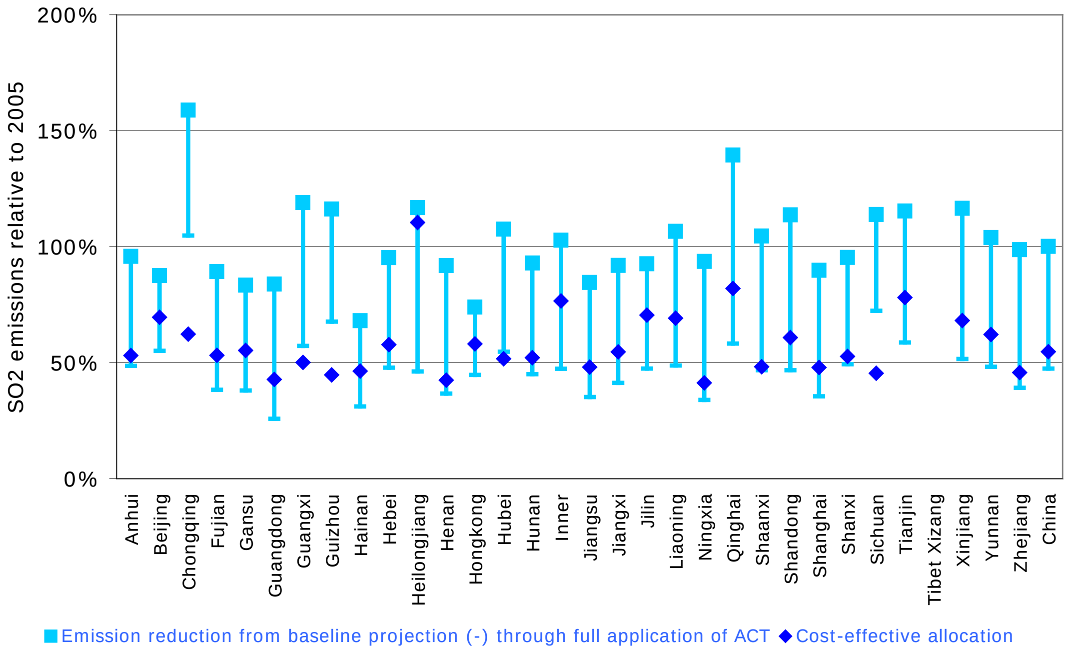

Figure 4.3: Cost-effective allocation of SO_2 emission reductions (diamonds) compared to the reductions from an across-the-board application of advanced control technologies for large sources (ACT) in 2030 (dashes). The blue squares indicate the level of baseline emissions resulting from the implementation of current emission control legislation.

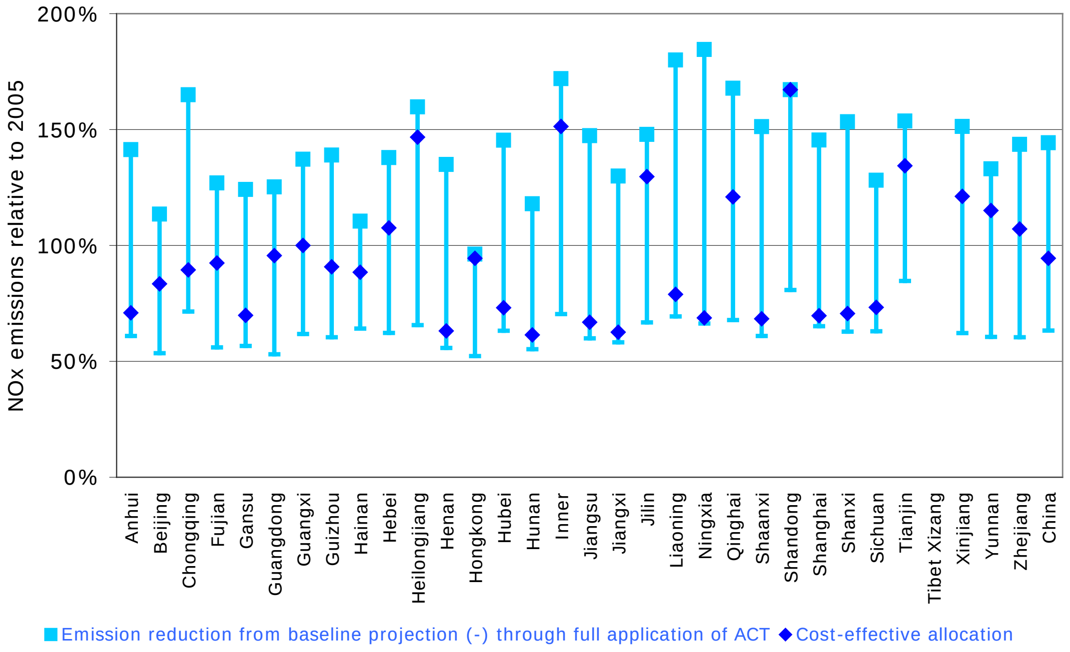

Figure 4.4: Cost-effective allocation of NO_x emission reductions (diamonds) compared to the reductions from an across-the-board application of advanced control technologies for large sources (ACT) in 2030 (dashes). The blue squares indicate the level of baseline emissions resulting from the implementation of current emission control legislation.

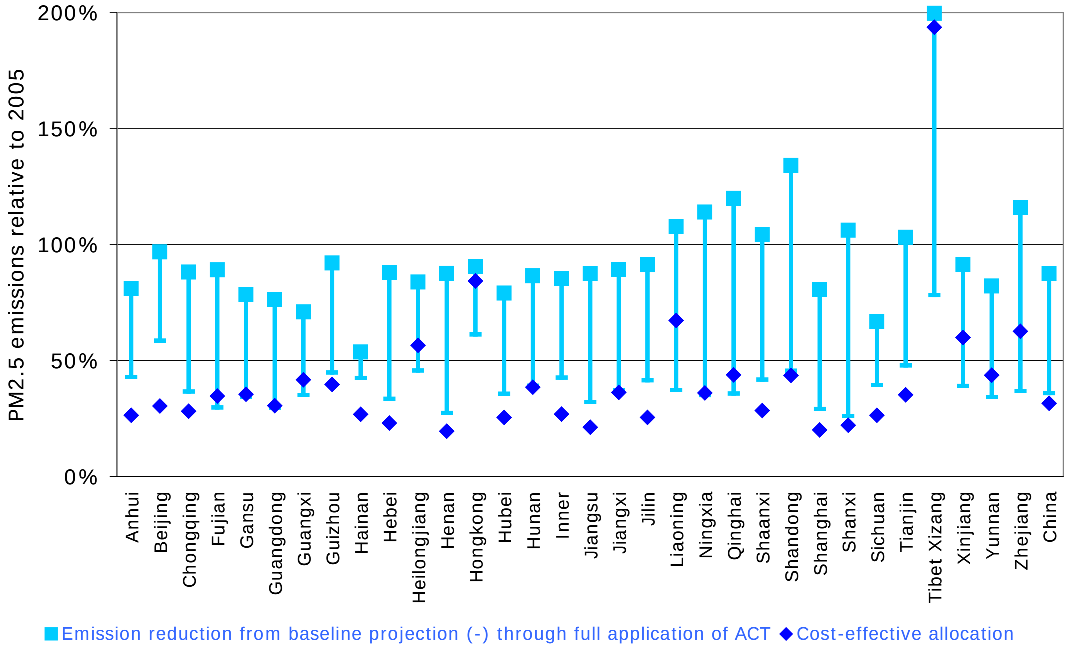

Figure 4.5: Cost-effective allocation of PM2.5 emission reductions (diamonds) compared to the reductions from an across-the-board application of advanced control technologies for large sources (ACT) in 2030 (dashes). The blue squares indicate the level of baseline emissions resulting from the implementation of current emission control legislation.

In terms of sectors, a cost-effective approach allocates more resources to control emissions from households. This transfer acknowledges the fact that (i) there is a significant potential for cheap emission reductions in the domestic sector that are not employed in the ACT strategy which focuses on emissions from large sources such as power plants and industrial boilers, and (ii) that emissions from low-level sources such as households make a larger contribution to population exposure than emissions from the high stacks of large sources. The environmental benefits of these additional controls of emissions from households allow less stringent emission controls in the power sector, which reduces the additional costs (on top of the CLE case) in this sector by one third. Also the need for pollution controls for industrial sources is substantially reduced, with costs declining by 75 percent. Further tightening of emission standards for mobile sources beyond what is already required by current legislation, though technically possible, turns out to be an economically inefficient means for improving health effects of air pollution as long as basic measures for controlling household emissions are not adopted. Overall, in such a cost-effective allocation, costs of additional measures that would cut health impacts by 43 percent would be 80 percent lower than in the case where advanced emission control technologies are applied to all sources across the board (Table 4.7).

Table 4.7: Emission control costs by sector in 2030, for the Current Legislation (CLE) case, the scenario with across-the-board application of advanced control technologies (ACT) and the cost-effective allocation determined with the GAINS model (OPT), in billion €/yr

	Total air pollution control costs			*Costs of additional measures on top of current legislation*	
	CLE	ACT	OPT	ACT	OPT
POWER GENERATION	15.7	26.5	22.7	10.8	6.9
INDUSTRY	21.9	52.4	29.7	30.5	7.8
DOMESTIC	0.6	0.9	3.4	0.3	2.9
TRANSPORT	52.2	90.7	52.2	38.5	0.0
AGRICULTURE	0.0	0.3	0.0	0.3	0.0
OTHER	0.0	3.1	0.1	3.1	0.1
TOTAL COSTS	90.4	173.8	108.1	83.5	17.7
% OF GDP	0.68%	1.30%	0.81%	0.63%	0.13%

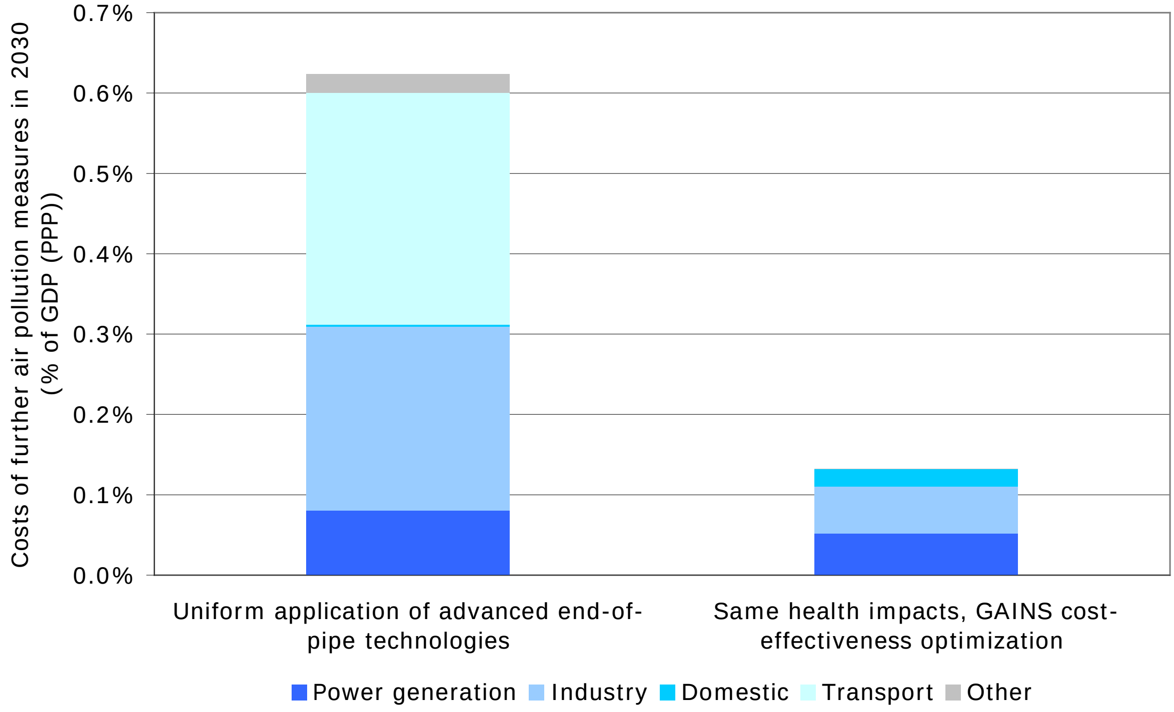

Figure 4.6: Costs of additional emission controls (beyond the measures required by current legislation) of the ACT scenario (left column) and the cost-effective allocation determined with the GAINS model (right column) in the year 2030. Both scenarios achieve a 43 percent reduction in health effects from PM pollution.

4.3 Cost-effective air pollution reductions including structural changes

It has been demonstrated in the above scenario that a targeted allocation of emission controls can lead to substantial cost savings. Obviously, the extent of possible cost savings is determined, inter alia, by the available scope for re-arranging emission control measures. In general, a larger scope for re-allocations increases the potential for cost savings. The portfolio of measures that is considered in the scenario above includes air pollution control measures in all sectors, and the cost savings of the optimized solution are achieved through re-allocation of these measures across sectors, pollutants and provinces.

However, air pollution emissions can be reduced not only through end-of-pipe measures. In general, air pollution emissions also decline if levels of anthropogenic activities that generate air pollution are reduced. Such changes could happen through technical measures, such as improved energy combustion efficiency, energy savings through, e.g., improved insulation, co-generation of heat and electricity, and through substitution of polluting fuels by cleaner fuels. Lower activity levels could also result from non-technical, behavioural changes, such as changes in transport modes, use of smaller vehicles, less living area heated, etc.

Since these non-technical measures require changes in personal life styles, they were traditionally beyond the portfolio of air quality managers. This also applies to most of the technical interventions that imply structural changes in the energy systems with direct implications on national energy policies. With growing concern about greenhouse gas emissions, however, such measures are now increasingly considered by policy makers who deal with the negative impacts of emissions to the atmosphere.

To explore the possible role of such structural measures in cost-effective air pollution control strategies, and their interactions with greenhouse gas emissions, the GAINS optimization also allows searching for least-cost solutions to achieve air quality targets that include these measures. Therefore, a scenario has been developed that explores the cost-effective portfolio of measures that, in 2030, cuts air pollution health impacts by 50 percent compared to the baseline case, with the portfolio including technical structural measures such as energy efficiency improvements through more efficient combustion processes and improved insulation, combined heat and power generation, fuel substitution and advanced clean coal technologies such as integrated gasification combined cycle (IGCC) plants. The portfolio, however, does not consider measures that change the behaviour of people, such as lower demand for transport and heating services, changes of transport modes, etc.

As shown in Table 4.8, a cost-effectiveness optimization that allows for structural changes leads to substantial overall cost savings in comparison to the corresponding optimization that excludes the possibility of structural changes. To halve health impacts in 2030, costs of pollution control measures (beyond what is required by current Chinese legislation) would shrink from €33.5 billion/yr (0.25% of GDP) to €20.9 billion/yr (0.16% of GDP). The cost-effective portfolio includes measures to increase energy efficiency in households and industry, enhanced co-generation of heat and electricity, and the substitution of coal and oil by renewable energy. These measures come at costs of €6.1 billion/yr, but their positive effects on air pollution emissions reduce the costs for further end-of-pipe air pollution control equipment that is required to meet the health target to €14.7 billion/yr (Figure 4.7).

Table 4.8: Costs of emission control measures for the GAINS optimization with air pollution measures only (left column) and the optimization with structural changes (billion €/yr)

	GAINS optimization with end-of-pipe air pollution control measures only	GAINS optimization with structural measures
END-OF-PIPE AIR POLLUTION CONTROL MEASURES:		
LARGE PLANTS, SO_2 CONTROLS	13.7	2.8
LARGE PLANTS, NO_X CONTROLS	9.9	6.1
LARGE PLANTS, PM CONTROLS	7.1	5.2
HOUSEHOLDS, PM CONTROL	2.9	0.6
SUB-TOTAL	33.5	14.7
STRUCTURAL MEASURES:		
ELECTRICITY SAVINGS, RENEWABLE ENERGY		0.6
CO-GENERATION OF HEAT AND POWER		2.9
ENERGY EFFICIENCY, INDUSTRY		0.4
ENERGY EFFICIENCY, HOUSEHOLDS		2.2
SUB-TOTAL		6.1
TOTAL	33.5	20.9

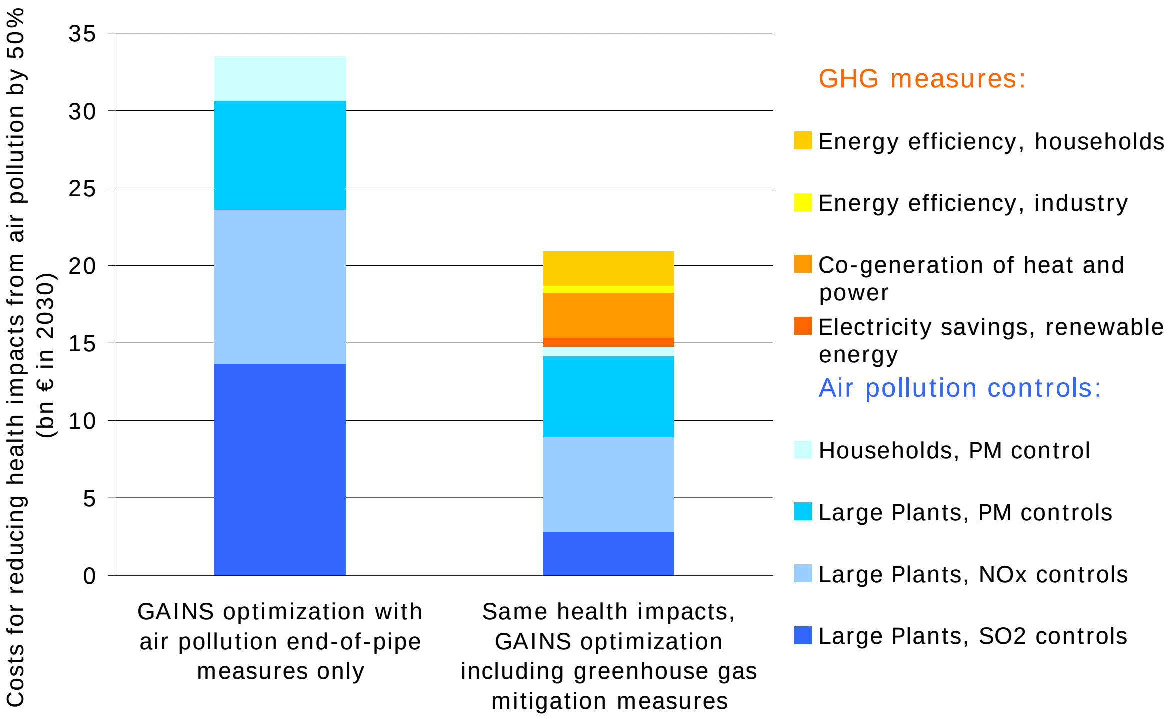

Figure 4.7: Costs for reducing health effects of air pollution in 2030 by 50 percent. Note that the optimization that includes greenhouse gas mitigation measures results in eight percent less CO_2 emissions as a side-benefit of air pollution control.

Inclusion of structural measures in the portfolio allow further reductions of primary particulate matter (PM2.5) beyond what end-of-pipe measures alone could deliver (Table 4.9). Given the fixed targets on health effects, the nine percent lower PM2.5 emissions relax the requirements for SO_2 and NO_x controls, so that emissions of these pollutants could be 10 percent higher than in the end-of-pipe only case. This reduced need for cuts in SO_2 and NO_x emissions, together with the lower baseline emissions of SO_2 and NO_x, lead to more than 50 percent lower emission control costs.

It is important to mention that, because these structural measures reduce the levels of energy consumption, they also lead to lower greenhouse gas emissions. Therefore, the inclusion of structural measures in the pollution control portfolio leads, as a side-effect, to eight percent lower CO_2 emissions.

Table 4.9: Emissions in 2030, for the GAINS optimization with end-of-pipe air pollution measures only and the optimization with structural measures, in kilotons

	SO_2		NO_x		PM2.5		CO_2	
	End-of-pipe only	With structural measures	End-of-pipe only	With structural measures	End-of-pipe only	With structural measures	End-of-pipe only	With structural measures
POWER GENERATION	2968	3087	3197	4277	314	458		
INDUSTRY	7899	9746	5199	5608	996	1135		
DOMESTIC	1647	913	728	415	1248	686		
TRANSPORT	530	530	4251	4251	279	279		
AGRICULTURE	0	0	0	0	151	153		
OTHER	0	0	0	0	247	247		
TOTAL	**13043**	**14276**	**13374**	**14551**	**3235**	**2957**	**11282**	**10403**
DIFFERENCE TO END-OF-PIPE		9%		9%		-9%		-8%

4.4 Air pollution control through greenhouse gas mitigation strategies

As demonstrated above, certain greenhouse gas mitigation measures form part of a cost-effective portfolio of air pollution control measures. The question arises to what extent a strategy that aims at reducing greenhouse gas emissions would create positive co-benefits on air quality.

A scenario has been developed by the Chinese Energy Research Institute that outlines an alternative development of the energy system that responds to increased concerns on energy supply security and local environmental pressure. While the underlying assumptions on population growth and economic development are identical to those of the Baseline projection, the Alternative scenario quantifies the consequences of a wide range of practical policy interventions that aim at a more sustainable development path of the Chinese economy. The scenario assumes wide adoption of regulations and financial incentives to promote energy conservation and renewable energy and to accelerate the conversion of the Chinese economy towards less energy intensive industries. In particular, it is assumed that active promotion of new technologies and new efficiency standards for new buildings will increase energy efficiency in the end use sectors. New taxes on vehicles and energy consumption will reduce the growth in transport and energy demand, and the share of public transport in cities will be increased by 10-15 percent in 2030. The scenario also assumes the introduction of fuel-efficient vehicles (hybrid vehicle, compact cars, advanced diesel cars). The combustion efficiency of coal-fired power plants will increase to 40 percent by 2030.

With these assumptions, the Alternative scenario projects for 2030 26 percent less coal and 10 percent less oil consumption than the Baseline case. Natural gas consumption is 44 percent higher, and biomass use is increased by nine percent (Table 4.10, Figure 4.8).

Table 4.10: Fuel consumption in China in 2005 and in 2030, for the Baseline projection and the Alternative scenario (PJ)

	2005	2030 Baseline projection	2030 Alternative scenario
COAL	51315	91976	67985
OIL	11174	29350	26410
GAS	1836	5626	8094
RENEWABLES	1812	7926	8086
NUCLEAR	927	12157	12157
BIOMASS	8750	8013	8726
TOTAL	**75814**	**155048**	**131458**

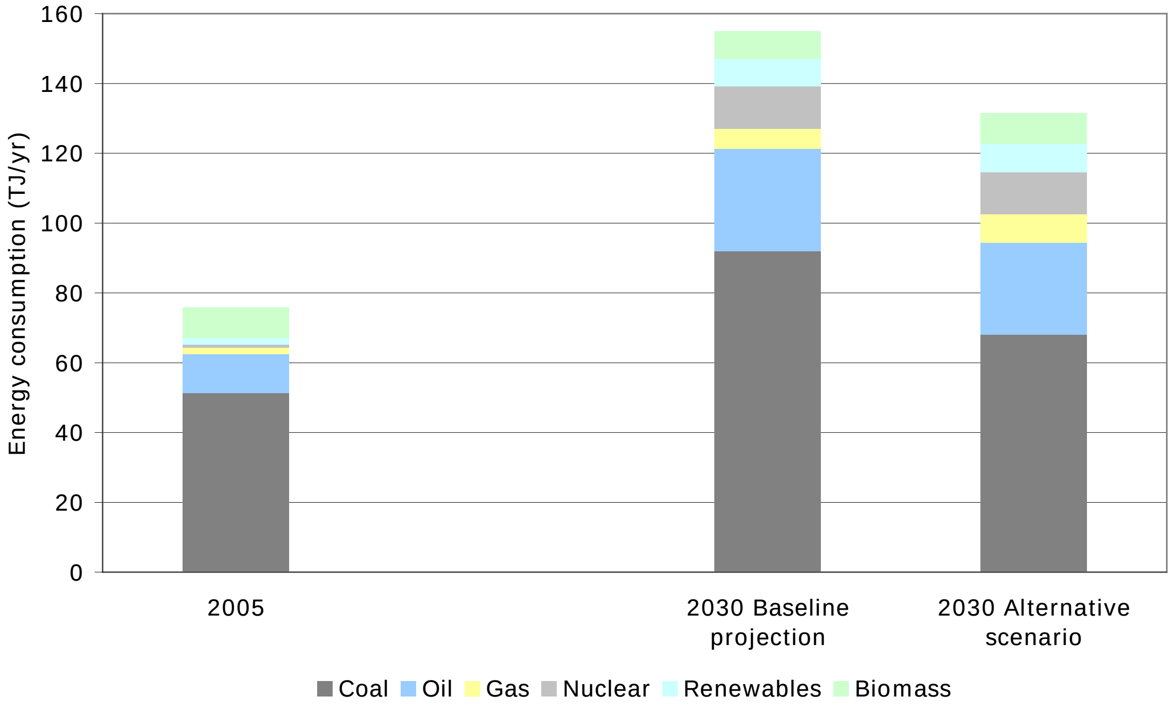

Figure 4.8: Energy consumption in China by fuel in 2005 and 2030, for the Baseline projection and the Alternative scenario

These lower consumption levels of carbonaceous fuels lead to distinctly lower emissions to the atmosphere. Assuming implementation of current emission control legislation in 2030, SO_2 and NO_x emissions are 21 and 19 percent lower than in the baseline projection because of less coal and oil consumption. The changed energy consumption structure also leads to lower emissions of particulate matter, however the difference (-9 percent) is less than for SO_2 and NO_x due to increased use of biomass. In addition, such a strategy would also cause 20 percent lower CO_2 emissions than the baseline projection (Table 4.11).

Table 4.11: Emissions of the Baseline projection and the Alternative scenario in 2030

	SO_2 (kt)		NO_x (kt)		PM2.5 (kt)		CO_2 (Mt)	
	Baseline	Alternative	Baseline	Alternative	Baseline	Alternative	Baseline	Alternative
POWER GENERATION	10758	8349	7592	5711	1650	1259	4802	3599
INDUSTRY	17499	14215	11645	9819	5340	5085	4716	3973
DOMESTIC	2769	1870	905	766	2728	2426	465	341
TRANSPORT	529	441	4251	3535	279	229	962	834
AGRICULT.	26	26	24	24	878	878	0	0
OTHER	0	0	0	0	258	258	336	253
TOTAL	**31581**	**24901**	**24417**	**19855**	**11133**	**10136**	**11282**	**9001**
DIFFERENCE TO BASELINE		-21%		-19%		-9%		-20%

Obviously, such lower emissions cause lower health impacts through reduced levels of PM2.5 in ambient air. It is estimated that the Alternative scenario reduces the loss in statistical life expectancy that is attributable to PM2.5 to 34 (18-46) months, compared to 39 (21-53) months of the Baseline projection, i.e., by 13 percent.

It should be mentioned that these lower emissions and health impacts occur as a mere side benefit of the assumed energy policy measures, and not of stricter air pollution emission control legislation. In fact, such an alternative energy strategy would reduce costs for implementing current air pollution legislation by €13 billion/yr or 0.1 percent of GDP (Table 4.12 These saving are caused by the lower levels of coal and oil consumption which also require fewer installations of air pollution control equipment.

Table 4.12: Air pollution control costs for implementing current Chinese legislation to the activity levels of the Baseline projections and the Alternative scenario in 2030 (billion €/yr)

	Baseline projection	Alternative scenario
POWER GENERATION	15.7	11.8
INDUSTRY	21.9	18.4
DOMESTIC	0.6	0.4
TRANSPORT	52.2	46.9
AGRICULTURE	0.0	0.0
OTHER	0.0	0.0
TOTAL	**90.4**	**77.5**
% OF GDP	0.68%	0.58%

At the moment the differences in costs between an energy policy that follows the Baseline projection and a strategy along the lines of the Alternative scenario cannot be quantified with the GAINS model. However, a comprehensive evaluation of the costs and benefits of these policy alternatives must include the cost savings from reduced air pollution controls as well as the health (and climate) benefits that result from lower emissions (Figure 4.9).

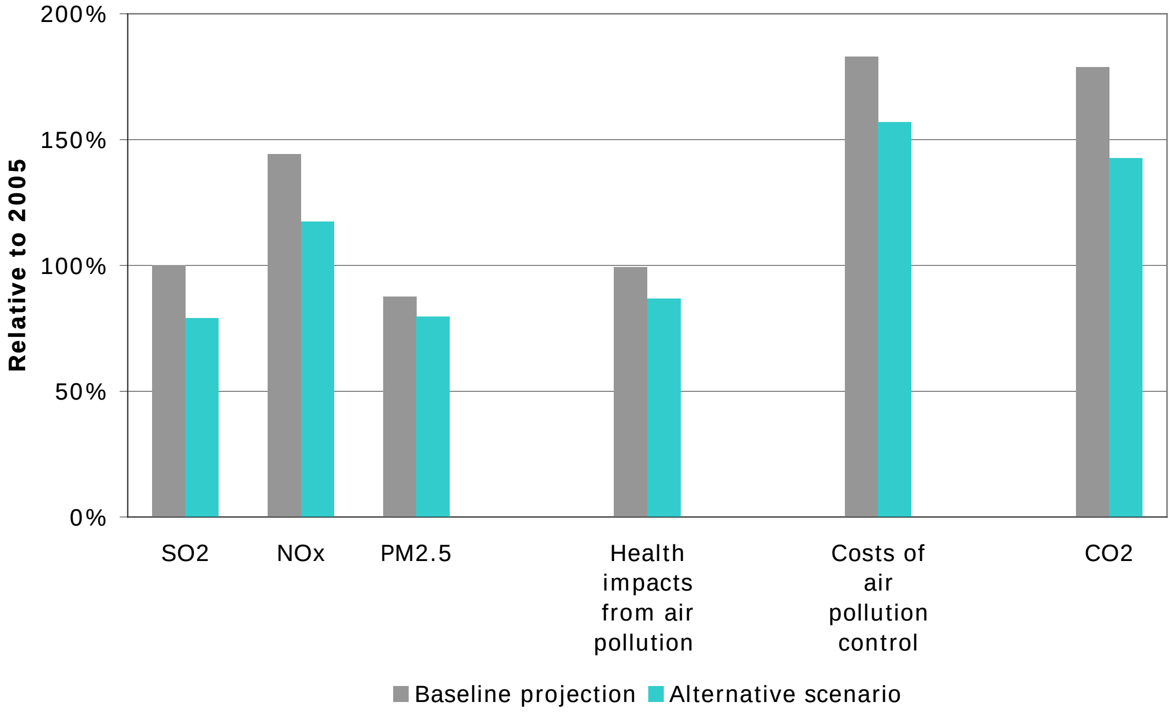

Figure 4.9: Comparison of key indicators of the Baseline projection and the Alternative scenario for 2030

5 Conclusions

Current and future economic growth in China will counteract ongoing efforts to improve air quality through controls of sulphur dioxide (SO_2) emissions from large stationary sources and nitrogen oxide (NO_x) emissions from vehicles. Unless further air pollution policies are implemented, the increase in coal consumption that should fuel additional industrial production and provide more electricity to a wealthier population will largely compensate the positive effects of current efforts to control SO_2 emissions in China. The lack of regulations for controlling emissions of NO_x from large stationary sources is expected to lead to a 30 percent increase in China's NO_x emissions despite the tight emission control legislation that has been recently imposed for mobile sources. Thereby, without further air pollution control policies, negative impacts on human health and vegetation that are currently felt across China will not substantially improve in the coming decades. For instance, it is estimated that present exposure to fine particulate matter (PM2.5) is shortening life expectancy of the Chinese population by approximately 40 (21-53) months, and that it would stay at that level in a business-as-usual case for the coming decades. Emissions of greenhouse gases that contribute to global climate change would increase by approximately 80 percent by 2030.

Yet, advanced emission control technologies are available to maintain acceptable levels of air quality despite the pressure from growing economic activities. Fully applying existing technical end-of-pipe emission control measures in China can lead to substantial improvements in air quality. It is estimated that negative health impacts could be reduced by 43 percent by 2030 by applying such advanced emission control technology to all large sources in China. However, such an undifferentiated across-the-board approach would impose significant burdens on the economy, involving an additional expense of 0.63 percent of GDP.

In contrast, a cost-effective emission control strategy developed with the GAINS optimization tool that selectively allocates specific reduction measures across economic sectors, pollutants and regions, could achieve equal air quality improvements at only 20 percent of the costs of a conventional across-the-board approach. An integral element of such an air pollution control strategy will be measures to eliminate indoor pollution from the combustion of solid fuels. The investment will also reduce crop losses by around 50 percent and have far ranging positive impacts on the environment, but will not result in positive side-effects on greenhouse gas emissions.

Well-designed air pollution control strategies can also reduce emissions of greenhouse gases. An optimized scenario developed with the GAINS model demonstrates that low carbon strategies result in lower emissions of sulphur dioxide (SO_2), nitrogen oxides (NO_x) and fine particulate matter (PM) at no additional costs. GAINS estimates that each percent of CO_2 reduction will typically reduce health impacts from fine particulate (PM) air pollution by one percent.

This also means that, for achieving given targets on ambient air quality, the cost of air pollution can be further reduced by adopting certain low carbon measures. A GAINS scenario demonstrates that the additional costs of some climate-friendly measures, e.g., energy efficiency improvements, co-generation of heat and power, fuel substitution, integrated coal gasification combined cycle (IGCC) plants, etc., are more than compensated for by savings in air pollution control equipment. By selecting a smart mix of measures to simultaneously cut air pollution and greenhouse gas emissions, China can almost halve air pollution control costs as well as lower greenhouse gas emissions by eight percent.

For policymakers, industry, NGOs and researchers wishing for more information and to conduct independent analyses, the GAINS-Asia model and documentation is freely available online at http://gains.iiasa.ac.at.

References

ADB (2007). Key Indicators 2007: Inequality in Asia. Asian Development Bank, Manila, Philippines, http://www.adb.org/Documents/Books/Key_Indicators/2007/default.asp

Amann, M., I. Bertok, J. Borken, A. Chambers, J. Cofala, F. Dentener, C. Heyes, L. Hoglund, Z. Klimont, P. Purohit, P. Rafaj, W. Schöpp, G. Toth, F. Wagner and W. Winiwarter (2008a). GAINS-ASIA. A tool to combat air pollution and climate change simultaneously. Methodology report. International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria,

Amann, M., I. Bertok, J. Borken, A. Chambers, J. Cofala, F. Dentener, C. Heyes, J. Kejun, Z. Klimont, M. Makowski, R. Matur, P. Purohit, P. Rafaj, R. Sandler, W. Schöpp, F. Wagner and W. Winiwarter (2008b). GAINS-Asia. A tool to combat air pollution and climate change simultaneously., International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria,

Amann, M., R. Mathur, I. Bertok, J. Borken, J. Cofala, C. Heyes, Z. Klimont, P. Purohit, P. Rafaj, W. Schöpp, F. Wagner and W. Winiwarter (2008c). GAINS-Asia. Scenarios for cost-effective control of air pollution and greenhouse gases in India. International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria,

Barker, T., I. Bashmakov, A. Alharti, M. Amann, L. Cifuentes, J. Drexhage, M. Duan, O. Edenhofer, B. Flannery, M. Grubb, M. Hoogwijk, F. Ibitoye, C. J. Jepma, W. A. Pizer and K. Yamaji (2007). Mitigation from a cross-sectoral perspective. Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, USA, Cambridge University Press.

Fischer, G., T. Ermolieva and H. van Velthuizen (2006). Livestock Production and Environmental Risks in China: Scenarios to 2030., International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria,

Hordijk, L. and M. Amann (2007). How Science and Policy Combined to Combat Air Pollution Problems. Environmental Policy and Law **37**(4): 336-340.

Huang, J., L. Zhang, Q. Li and H. Qiu (2003). CHINAGRO project: National and Regional Economic Development Scenarios for China's Food Economy Projections in the Early 21st Century., Center for Chinese Agricultural Policy, Chinese Academy of Sciences. , Beijing, China,

IEA (2007). World Energy Outlook. International Energy Agency, Paris, France,

Nakicenovic, N., R. Swart, N. Nakicenovic, J. Alcamo, G. Davis, B. d. Vries, J. Fenhann, S. Gaffin, K. Gregory and A. Gruebler (2000). Special Report on Emissions Scenarios. ISBN 0-521-80493-0, Working Group III of the Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge, UK,

Smith, K. R., S. Mehta and M. M. Feuz (2004). Indoor air pollution from household solid fuel use. Comparative quantification of health risks: Global and regional burden of disease attributable to selected major risk factors. M. Ezzati, A. D. Lopez, A. Rodgers and C.J.L. Murray. Geneva, Switzerland, World Health Organization**:** 1435–1493.

Swart, R., M. Amann, F. Raes and W. Tuinstra (2004). A Good Climate for Clean Air: Linkages between Climate Change and Air Pollution. An Editorial Essay. Climatic Change **66**(3): 263-269.