6. Application of AIM/Local Model to India using Area and Large Point Sources

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Summary. India's emissions inventory estimates indicate that Large Point Sources (LPS) contribute above 60% of CO_2 and SO_2 emissions. Uneven distribution of energy resources, unbalanced regional development and the present high economic growth has led to emission patterns with dispersed hotspots. The policy making to address the environmental concerns thus rests on the assessment of future emissions and the options to mitigate them. The paper shows, using AIM/Local model with GIS interface, that Indian CO_2 emissions shall continue to rise steadily till 2030, whereas the SO_2 emissions shall decline after 2020, creating a natural decoupling of Greenhouse Gas (GHG) and local emissions. The carbon mitigation analysis, under three global policy regimes, indicates substitution of coal by gas, besides pushing energy efficient and low carbon technologies. Under all the scenarios, LPS contribute a major share of emissions, with industrial centers and large cities growing into major hotspots of emissions. Paper suggests that these spots would be the major focus of future emissions mitigation policy analysis for applications of formal tools like the AIM/Local model.

6.1 Introduction

Industrial development has contributed significantly to economic growth in India over last few decades; however, industrialization has not been uniform. Large and modern urban centers coexist with traditional rural and agrarian economy. The varying sectoral growth rates, consumption patterns and resource endowments have led to widely different regional and sectoral emission distributions. Some of the regions have experienced fast industrialization, and increasing air pollution in such areas is becoming an important environmental issue. Coal based thermal power plants, steel and cement plants have been major contributors to CO_2 and SO_2 emissions emanating from fossil fuel consumption. Transport sector is a major contributor to urban air pollution. Emissions from large industries are growing at a rate faster than the national average. High concentration of pollution in India is not due to a lack of sound environmental policy regime, but due to a lack of implementation at the local level. The LPS emissions are growing much faster than the national average due to growing population, increasing urbanization and higher consumption levels. Therefore, there is a need to estimate

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future emissions both from LPS and from area sources to prepare an implementation plan for emission mitigation.

This paper presents the analysis of Indian emissions using AIM/Local model. Indian emissions inventory for carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulfur dioxide (SO_2) and nitrogen oxides (NO_X) at sectoral levels for 1995 and 2000 shows that LPS contributed to Indian CO_2 and SO_2 emissions to a large extent (above 60%) while for the other gases LPS contribution was below 10% (Garg *et al.* 2002). Therefore, we have projected CO_2 and SO_2 emissions temporally and regionally using AIM/Local model at area and LPS levels. 382 LPS and 466 area sources (Indian districts) are covered for the base year 2000. New LPS are added to reach 457 (2010), 523 (2020) and 587 (2030) based on present investment proposals for new plant installations, retrofitting and expansion options for the existing plants, and policy dynamics. The LPS share in Indian CO_2 emissions is projected to increase marginally from 64% to 65% in 2030 while that of SO_2 increases from 62% to 70% up to 2020 and decreases marginally to 66% in 2030. The total CO_2 emissions in India are projected to increase almost 3.15 times to 2945 Mt-CO_2 in 2030. However SO_2 emissions grow only about 1.15 times during the same period to 5.8 Mt-SO_2 in 2030 indicating a disjoint between GHG and local pollutant emissions in future. This is mainly due to adoption of flue gas desulfurisation and clean coal technologies in the power sector, and considerable reduction in sulfur contents in petroleum products. Some of these policy dynamics are already visible in India. The paper also demonstrates this Indian emission dynamics and would be useful for policy makers and researchers.

6.2 Methodology

The emission sources may be broadly classified as LPS, area sources and line sources (mainly for transportation sector). In the present analysis, we have combined the area and line sources since activity data for transport sector at line source level is not available. The combined representation is called area sources. The aggregate national emissions are the sum of LPS and area source emissions. For future emission projections at LPS and area source levels, AIM/Local model with Geographical Information System (GIS) support has been used.

The AIM/Local model follows the approach of linear programming to find an optimal solution by selecting a combination of technologies with the least cost while satisfying the given constraints of fulfilling the demand and meeting the environmental targets and/or energy supply constraints in the specific region (AIM Project Team 2002). This model estimates the emissions from the LPS and area source, which can be used to calculate the total emissions from a region. Emission calculation methodology used in AIM/Local model is in line with the recommended methodology of the Intergovernmental Panel on Climate Change (IPCC 1996) and follows a similar approach as used by (Li *et al.* 1999) and (Garg *et al.* 2001a, 2001b). A detailed description of the emission estimation methodology used in AIM/Local model is given in the Appendix.

Indian AIM/Local model is developed for five major sectors namely power generation, industrial, transport, residential and agriculture sectors. The choice of these sectors is based on their importance in the national energy consumption. The industrial sector covers fifteen major industry types. Each sector is modeled with considerable technological details about consumption of different energy forms, emission of various gases, cost components, and technological shares. Power generation and industrial sectors provide all the LPS for the analysis whereas the other sectors have been modeled as area sources.

The AIM/Local model, suitable for estimating future emissions from LPS and area sources, is demand driven. The enduse sectoral demands in turn depend upon national macro-economic growth projections. Based on the last 30-year time series GDP data, government projections and expert opinion, the Indian GDP is assumed to grow in real terms by 6% per annum on an average during 2000-2015, by 5% during 2015-2025, by 4% during 2025-2035 and by 3% in the later half of the 21st century under the reference scenario. The Indian GDP grows 4.8 times at an annual rate of 5.2% and population rises from the present 1 billion to 1.35 billion between the years 2000 to 2030 (UN 1998) indicating a four-fold increase in per capita income levels.

The industrial enduse sector demands saturate in the long run following a logistic model. This is divided into LPS and area demand. Excess demand over and above the capacity of the LPS has been taken as area source demand in case of industries where the total estimated national demand exceeded the total capacity of all the LPS considered. The autonomous energy efficiency improvements (AEEI) in enduse technologies supplying these demands capture improvements due to better management practices, learning curve, improved infrastructure, retrofitting for the existing demand technologies and incremental technological interventions.

The AIM/Local model also captures the present policy dynamics to reduce anthropogenic air pollution by various measures including fuel quality improvements, adopting cleaner technologies and stricter enforcement of emission regulations. Fuel quality improvement includes coal beneficiation, increased use of imported coal (lower ash and higher calorific value than the average Indian coal), and reduction in sulfur contents of petroleum products.

Production quantity for an LPS has been estimated on the basis of the sectoral demand elasticity and the past production trends of the plant, wherever available. Information regarding the new LPS till year 2010 has been taken from various data sources like CMIE (2002b) and policy documents of the government. New LPS locations beyond the year 2010 have been estimated based on past development trends, retrofitting expansion options for the existing plants, studies related to suitability of industrial locations in India, and present policy dynamics. These are however indicative and not conclusive since the actual LPS locations may vary as future unfolds.

6.3 Data Sources and Coverage

Many diverse data sources were utilized since there is no comprehensive database covering all the types of emitters for India. These included published documents of the Government of India, state governments, government organizations and institutions, industry federations and autonomous organizations covering various sectors and fuels (Garg *et al.* 2001a, 2001b, 2002). Future LPS data was mainly taken from published reports and databases like CMIE (2002a, 2002b). These provide status information of the various planned investment projects in India (power, refineries, cement, steel and fertilizer plants, etc.) till almost 2010. Coupled with the retrofitting and capacity augmentation options for the existing plants, present policy directives of the government and expert opinion, LPS information for the next 30 years was assimilated. We have tried to cross verify each existing LPS data using more than one data source providing a profound richness and robustness to the base data. We have projected CO_2 and SO_2 emissions in the present paper since LPS have a dominant share only for these two emission types. Table 1 provides the LPS coverage over the years.

6.4 Results

6.4.1 Reference scenario

The reference scenario assumes the dynamics-as-usual, i.e. continuation of macro-economic (including structural changes in the economy), demographic and energy sector trends (such as autonomous energy efficiency improvements and penetra-

Table 1. Large point source coverage over the years for India

Sector	Sub-sectors	LPS covered			
		2000	2010	2020	2030
Energy	Power (coal & oil)	82	111	131	150
	Power (natural gas)	12	17	20	23
	Steel	10	16	22	28
	Cement	85	98	110	123
	Fertilizer	31	41	52	62
	Paper	33	38	43	48
	Sugar	28	28	29	30
	Caustic soda	19	21	23	26
Industrial processes	H_2SO_4 manufacturing	63	64	66	68
	Aluminium	3	4	5	5
	Copper ore smelting	8	9	10	11
	Lead ore smelting	5	6	7	8
	Zinc ore smelting	3	4	5	5
Total		382	457	523	587

tion of clean and renewable fuels and technologies), as well as government policy trends. There are no direct climate change policy interventions in the reference scenario.

The reference scenario analysis shows that during 2000-2030, energy use will grow three times and carbon emissions from energy will grow 2.7 times (Fig. 1). Under the dynamics-as-usual, the energy system shall continue to depend on fossil fuels, primarily the domestic coal (Fig. 2). Between years 2000 and 2030, carbon intensity of GDP declines at 1.9% per year (Fig. 3). The improvement in carbon intensity is contributed mainly by the decline in energy intensity at 1.5% annual rate and the rest is contributed by the substitution of the share of coal in energy by gas and marginally by renewable energy. Future emissions of CO_2 and SO_2 for the reference scenario are shown in Table 2. Although CO_2 emissions grow annually at 3.4%, the SO_2 emissions rise at much lower rates. This is due to policies that are already under implementation as well as increasing public pressure on national policy makers for local pollutants, which is not the case for the GHG emissions. The CO_2 and SO_2 emission trajectories move in closer bands till 2010 due to continuation of existing vintages. Thereafter, while CO_2 emissions continue to rise, the SO_2 emissions begin to decline following the Kuznets curve phenomenon (Kuznets 1958). The GHG and local pollutant emissions are thus decoupled in future. SO_2 emission reduction happens from mandatory use of Flue Gas Desulfurisation (FGD) in large coal power plants, introduction of low sulfur diesel, washing of coal and stricter enforcement of local air quality regulations. These policies however do not affect the GHG emissions.

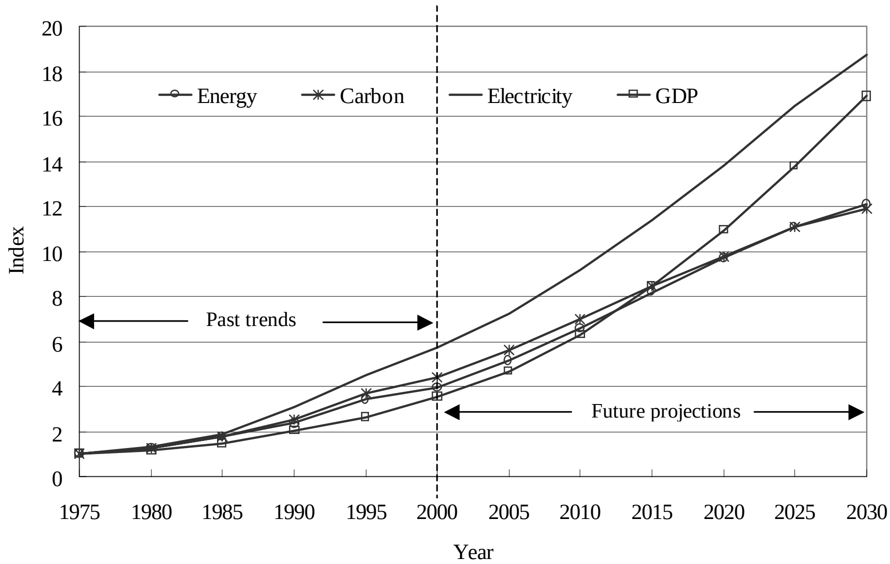

Fig. 1. Energy, carbon, electricity and GDP (reference scenario projections)

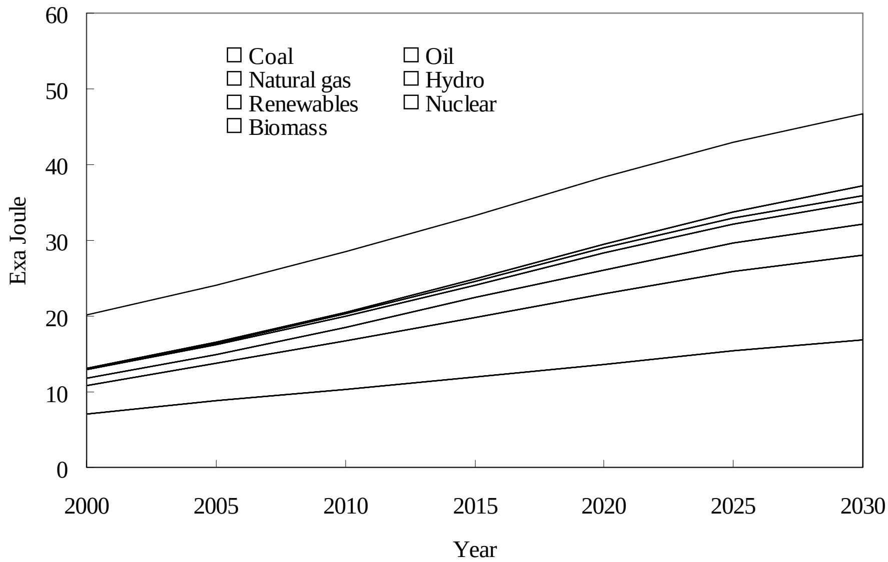

Fig. 2. Energy demand from 2000-2030 (reference scenario projections)

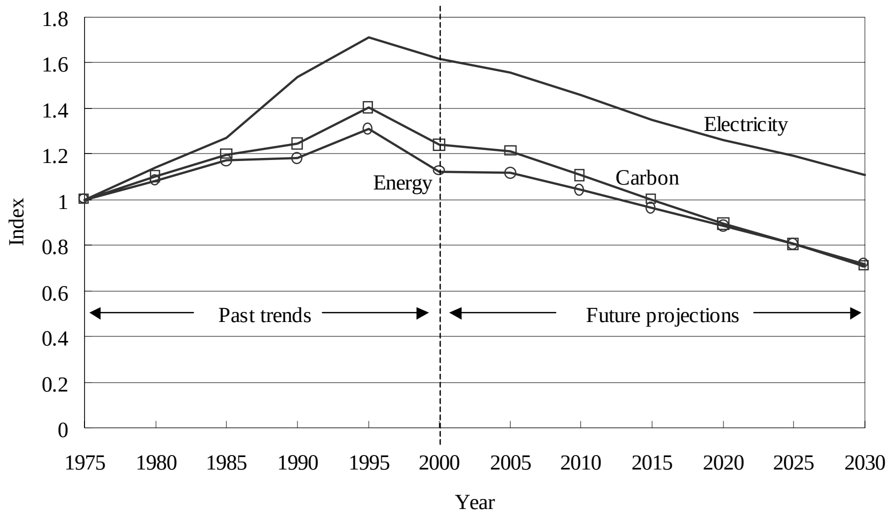

Fig. 3. GDP intensities of energy, electricity and carbon (reference scenario)

There is an interesting emission dynamics evolving in India and transport sector is at the center of this development. The sulfur content in the diesel oil supplied to the metropolitan cities (Delhi, Mumbai, Chennai and Kolkata) has been decreased during the year 2000 from 1% sulfur by weight to 0.25% by the Indian refineries as per the Indian government directives. The sulfur content has been further reduced to 0.05% by weight in Delhi by late 2001. This has resulted in an appreciable decrease in SO_2 emissions from the transport sector in these cities. These four cities account for almost 8% of all India diesel consumption in 2000. Diesel, in turn is almost 40% of the national petroleum product consumption and transport sector accounts for almost three fourths of this consumption. Although the effect of this emission dynamics may not be felt in the overall national SO2 emissions, which have continued to rise, the long-term implications are appreciable.

Besides these there has been recent Supreme Court judgment that has ordered Euro II standards to be followed for all new cars in India, which will be upgraded to Euro IV by 2005 (Mashelkar *et al.* 2002). While this is not very significant for SO_2 control, it shows the mind-set of the judiciary and policymakers to control local pollution. Moreover it is necessary to have low sulfur diesel for meeting the emission norms beyond Euro II. The reduction in SO_2 emissions would be further strengthened by another recent policy decision on mandatory washing of coal that is used 700 Km away from the mine mouth. This measure is aimed at reducing fly ash and also simultaneously reduces some sulfur. Since, over a third of coal is used beyond 700 Km, this measure is expected to start reducing SO_2 from coal use in near future. This policy dynamics manifests in a reduction in SO_2 emissions in future even though the absolute energy consumption, and therefore CO_2 emissions, continue to rise.

Coal remains the mainstay of the Indian energy system but its use becomes cleaner due to higher penetration of clean coal technologies (WB 1997). Coal consumption increases about 2.5 times during 2000-2030 from 310 Mt in 2000. About 90% of the Indian coal product consumption is by LPS for power generation and industry. Residential coal consumption (area sources) for cooking purpose is mainly limited to lower middle class households in semi-urban areas. The urban households normally use LPG and kerosene, while fuel wood, dung cakes and electricity are also consumed in small proportions. Commercial establishments like hotels and restaurants consume some coal for cooking but their consumption is miniscule in comparison to the LPS coal consumption. Biomass supplies the rural energy demand to a large extent with kerosene supplementing it partially.

The sectoral fuel consumption indicates continued dominance of power sector in coal use and transport in petroleum products with each having 70 percent share in 2030. Transport sector coal consumption is negligible for future years due to phasing out of coal based steam traction from Indian Railways. LPS dominate power sector consumption while transport sector has area source dominance. Power sector share in natural gas consumption increases to more than half from the present one third, caused by increasing competitiveness of Combined Cycle Gas Turbine technologies (CCGT) for electricity generation (Shukla *et al.* 1999).

Gas consumption is also LPS dominated and rises rapidly in industries like fertilizers and petro-chemicals. While the share of gas in primary energy still remains low, the trends suggest a rising penetration of gas, most of which would have to be imported.

The distribution range of LPS emission in the total national emissions is indicated in Table 2. The largest 50 LPS contribute almost 50% of all India emissions in 2000, which decreases to 41% in 2030 as the emissions from smaller LPS increase (Table 3). The CO_2 and SO_2 emissions from LPS and area sources over the years for reference case are illustrated in Fig. 4 and Fig. 5 respectively.

Table 2. Share of LPS emission in all India emissions

	Emission details	2000	2010	2020	2030
CO_2	Number of LPS	303	374	435	495
	LPS emissions (Mt-CO_2)	630	989	1418	1912
	All India emissions (Mt-CO_2)	983	1556	2189	2945
	LPS/total (%)	64	64	65	65
SO_2	Number of LPS	368	437	499	559
	LPS emissions (Mt-SO_2)	3.12	3.96	4.35	3.83
	All India emissions (Mt-SO_2)	5.02	5.87	6.25	5.77
	LPS/total (%)	62	67	70	66

Table 3. Distribution range of LPS emissions (% of all India emissions)

Largest LPS	CO_2 emissions				SO_2 emissions			
	2000	2010	2020	2030	2000	2010	2020	2030
1 to 25	35.2	32.5	31.0	31.5	37.1	38.0	37.3	32.5
26 to 50	11.5	11.0	10.9	11.0	12.0	12.8	13.0	12.4
51 to 75	5.7	5.4	5.7	5.6	5.2	5.6	6.0	5.9
76 to 100	3.7	3.9	4.1	4.2	3.1	3.5	4.0	3.9
101 to 200	6.7	7.8	8.6	8.7	4.2	5.8	7.2	8.2
All others	1.3	2.7	3.0	3.9	0.6	1.8	2.2	3.4

Table 4. LPS contribution to CO_2 energy sector emission (% of all India emissions)

Sector	2000	2010	2020	2030
Power	41.3	41.5	43.0	48.0
Steel	12.4	11.3	10.2	8.0
Cement	9.0	9.6	8.8	7.5
Fertilizer	0.7	0.3	0.2	0.2
Paper	0.4	0.5	0.5	0.5
Aluminum	0.1	0.2	0.2	0.3

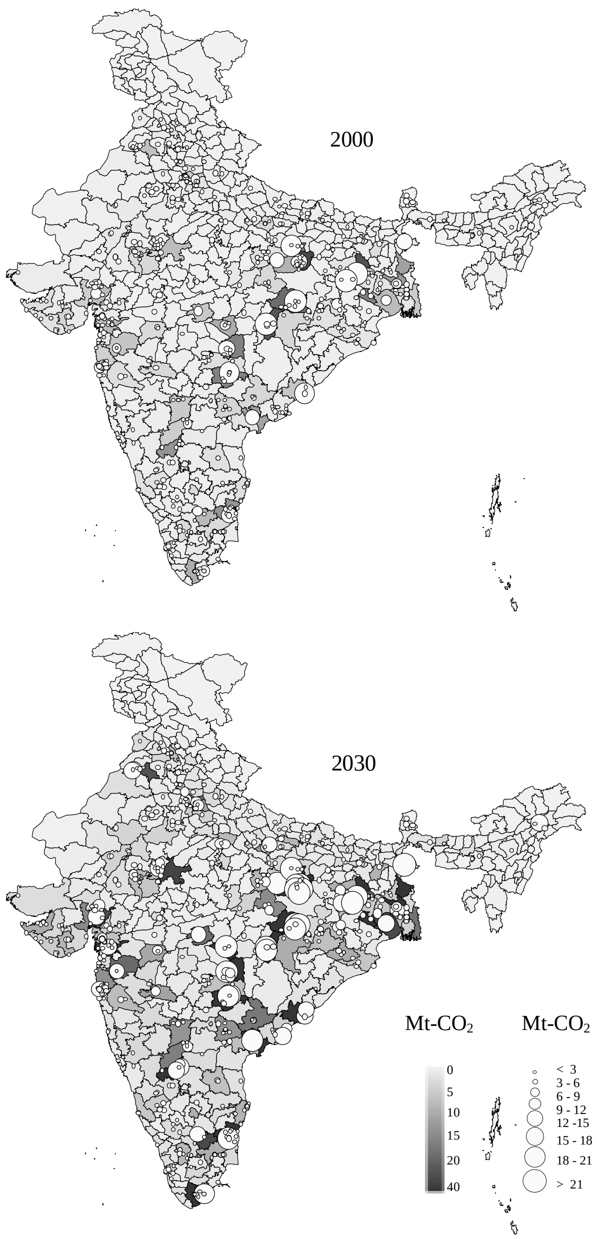

Fig. 4. Regional distribution of CO_2 emissions in India for 2000 and 2030 in reference scenario (see color plates)

Note: Circles show emissions from large point sources.

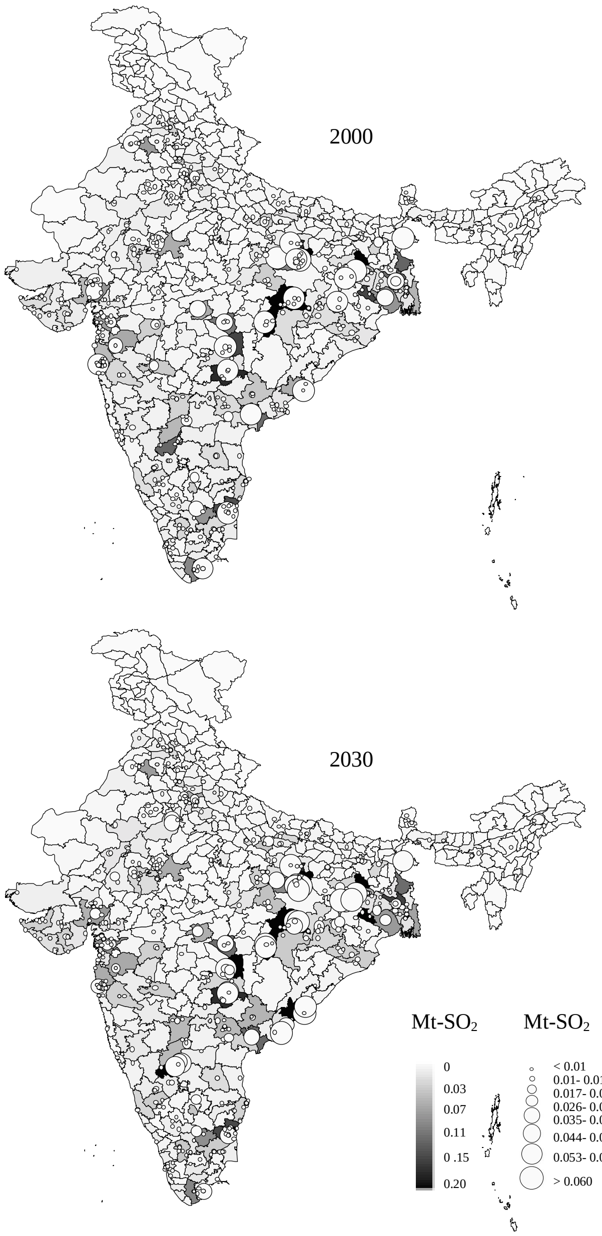

Fig. 5. Regional distribution of SO_2 emissions in India for 2000 and 2030 in reference scenario (see color plates)
Note: Circles show emissions from large point sources.

Table 5. LPS contribution to SO_2 energy sector emission (% of all India emissions)

Sector	2000	2010	2020	2030
Power	44.5	47.1	46.5	40.0
Steel	11.6	13.1	14.7	16.0
Cement	4.7	6.1	7.1	8.4
Fertilizer	0.5	0.2	0.1	0.1
Paper	0.5	0.7	0.9	1.2
Aluminum	0.3	0.3	0.4	0.5

The sectoral shares (Tables 4 and 5) indicate that LPS emissions would continue to be major contributors to national CO_2 and SO_2 emissions in future. The share of LPS in SO_2 emissions decreases marginally in the later years as compared to CO_2 emissions. This is because the SO_2 emissions from LPS as well as some area sources such as transport sector reduce considerably but the emissions from the small-scale industries like brick making, which depend on coal, continue to grow. These small establishments though essentially point sources are spread all over and have been classified as area source in the model. This reduction of LPS share in SO_2 emissions further indicates that the disjoint between the GHG and local pollutant emissions, discussed earlier, is unfolding gradually in India.

6.4.2 Climate change mitigation scenarios

India does not have any GHG emission mitigation commitments presently. However rising emission trends necessitate an understanding and analysis of carbon mitigation policy options for India. These policies prompt technology and fuel substitution by changing the relative costs of competing fuels in favor of those with lower carbon contents. Carbon mitigation would therefore require technological transformation of Indian energy system. Efficiency improvement measures, cleaner technology and cleaner fuels will penetrate faster and infrastructure to facilitate these has to be built. This will need investments in infrastructure to support the new technologies and reforms to remove the barriers for their penetration. Societies with strong reduction commitments would therefore have to start thinking differently.

The reference case provides a platform for analyzing implications of alternate carbon mitigation scenarios for India. The present analysis considers a reference scenario that assumes a world that is akin to the B2 scenario of Special Report on Emissions Scenarios (SRES) (IPCC 2000). Climate intervention scenarios are then considered that presume alternate Kyoto-plus regimes aimed at stabilizing long-run concentrations at 550, 650 and 750 parts per million volume (ppmv) of CO_2 concentrations. The global emission budgets are as per SRES and have been allocated between world regions, with around 7.5% share of global carbon emissions as the cumulative emission budgets for India during the 21st century. The present analysis is for the period 2000-2030.

Some important results are indicated in Table 6 and Fig. 6. Inertia of existing technological stock in the energy system prevents significant fuel substitution till the year 2010 for meeting carbon mitigation targets and coal continues to dominate the energy system. However coal consumption declines drastically in the long-term for 550 ppmv emission targets. Decline in gas consumption in medium and long term in this scenario is due to increasing penetration of carbon free technologies like renewable and nuclear for power generation. However coal is mainly substituted by natural gas in power sector. While natural gas exhibits early penetration, renewable penetration is late due to their high initial investment costs. Due to the rising gas prices with higher use of gas in later years, the renewable energy penetration increases with rising mitigation targets.

Table 6. Results of climate change policy scenarios

Parameter	750 ppmv			650 ppmv			550 ppmv		
	2010	2020	2030	2010	2020	2030	2010	2020	2030
Coal #	-2	-5	-18	-4	-17	-32	-9	-29	-51
Gas #	+1	+3	+13	+1	+10	+13	+1	+18	-9
CO_2 (Mt-CO_2)	1408	1907	2431	1327	1775	2229	1254	1621	1998
SO_2 (Mt-SO_2)	5.82	6.13	5.43	5.67	5.39	4.87	5.42	4.79	3.81

Percentage changes over the reference scenario consumption.

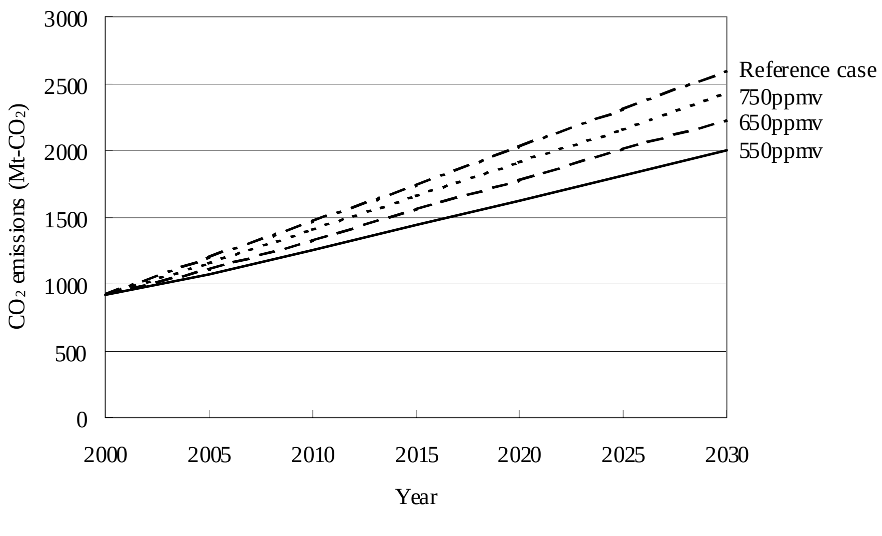

Fig. 6. Carbon dioxide stabilization scenarios (2000-2030)

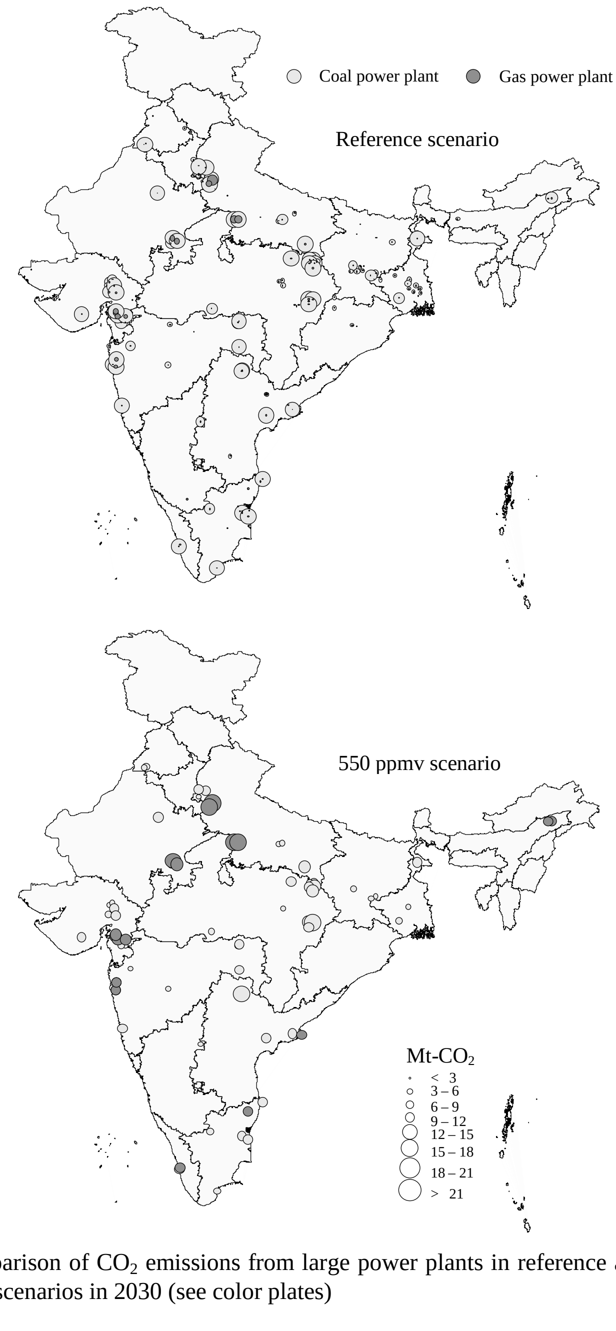

Fig. 7. Comparison of CO_2 emissions from large power plants in reference and 550 ppmv stabilization scenarios in 2030 (see color plates)

Table 7. Supply and demand side contributions to emission reductions (%)

Mitigation scenario		2010	2020	2030
750 ppmv	Supply side	32	53	71
	Demand side	68	47	29
650 ppmv	Supply side	36	56	72
	Demand side	64	44	28
550 ppmv	Supply side	40	63	75
	Demand side	60	37	25

Analysis of carbon mitigation scenarios provides some useful insights regarding energy supply and demand side contributions to emissions reductions (Table 7). In the early periods (up to 2010), the demand sectors show more flexibility than the supply side by contributing more to carbon emission reduction since enduse technological stock turnover is faster due to their relatively shorter lifetimes. But in later periods, the supply side contribution increases, finally reaching almost a three-fourth share in the total mitigation in 2030. These, however, include emission reduction due to lower power generation requirements as demand side energy efficiencies improve.

The inertia of supply side technology turnover is due to their much longer lifetimes, high investment requirements and longer gestation period for infrastructure development. The supply side mitigation options are primarily associated with fuel switching from coal to natural gas. Since India is not endowed with much of natural gas resources, most of this gas would be imported and therefore has national energy security issues attached. Long-term options include penetration of carbon-free technologies like nuclear and renewable technologies. Judged from a market perspective, there are large inefficiencies on the demand side due to capital shortages, risk, high transaction costs and weak financial markets. The supply side is better organized and has lower inefficiencies. This dynamics is demonstrated by the spread of power sector LPS emissions in future (Fig. 7). The fuel switching from coal to gas, especially in the coastal areas and in the demand centers of northern India is apparent. There are more gas-based power plants in the 550 ppmv case as compared to the reference case. Gas based power plants contribute 15% of power sector CO_2 emissions in 2030 in the reference case while it almost doubles in 550 ppmv case despite the fact that the emissions from an equivalent gas based power plant are 40% lower than a coal plant (Garg and Shukla 2002). SO_2 reduction is even stronger in the 550 ppmv case since gas emits no sulfur.

Carbon mitigation also acts as a push policy for cleaner technologies especially in the industrial sectors. Autonomous energy efficiency improvements provide the initial options for carbon mitigation in India since the average energy efficiencies in most sectors are well below international averages. Improved oxygen furnace with gas recovery replaces existing open hearth furnace for steel production, improved dry process with pre-heaters and pre-calcinators replaces/augments the existing wet/dry process in cement industry, vertical shaft and high draught kilns replace clamp type and Bull's trench kilns in brick industry, CNG and electric cars partially replace diesel and petrol cars etc.

6.5 Conclusions

Analysis of LPS emissions highlights sectors and plants where mitigation efforts should be targeted for cost-effectiveness. The main contributors to Indian emissions presently are about 70 LPS (50 power, 5 steel and 15 cement plants), thus offering a good opportunity for focusing mitigation efforts. Power sector is the predominant emission source for CO_2 and SO_2. Operational improvements (like heat rate reduction, excess air control etc.), better maintenance, reducing transmission and distribution losses in the power sector would go a long way in emissions mitigation. The other policy options are switching from coal to lower carbon content fuels like natural gas, sequestering the emitted carbon from LPS, increasing renewable and nuclear technology penetration etc. Carbon emission mitigation analysis under 750, 650 and 550 ppmv scenarios demonstrate this fuel shift.

Energy efficiency improvement measures in other sectors like steel, cement, caustic soda, sugar, brick making and fertilizer would improve productivity while reducing overall emissions. Demand side sectors contribute more to carbon emission mitigation in the short run while supply side (mainly power generation) contributes more in the long run. The longer life, higher investment requirements and longer gestation periods of supply side technologies as compared to the demand side explain this.

Apart from LPS, there are many small, moving and concentrated point sources like vehicles in urban transport. These are covered under area sources in the present analysis. Mitigation options have to be carefully planned for these sources since some of the above mentioned policy options, though useful for small but distributed sources as well, would not be cost-effective for them since implementation efforts would be substantial. For example, although transport sector sources contribute around one tenth to India's CO_2 equivalent GHG emissions and almost a third to NO_X emissions, their characteristics (large numbers and low emissions per source) necessitate huge mitigation efforts as compared to very focused mitigation efforts for LPS. However measures like improving diesel and gasoline quality and stricter vehicle emission norms will reduce local pollution levels and to a certain extent GHG emissions as well.

Transport sector emissions from Delhi are an interesting case for such analysis where introduction of low sulfur diesel in recent years reduced SO_2 emissions significantly. Subsequent shift to mandatory use of Compressed Natural Gas (CNG) in public vehicles further reduced sulfur and particulate emissions, besides reducing carbon emissions. These policies, introduced by the Indian Supreme Court orders, are not necessarily cost-effective. A superior mix of policies would minimize long-term cost for achieving the desired air quality standards at city level. The AIM/Local model is well suited to analyze future emission from all sectors and to derive such policies.

The results from our study have demonstrated that the LPS would continue to be responsible for considerable part of the Indian carbon emissions. Power generation and industry would contribute almost 75% of CO_2 emissions. Since these sectors have a natural dominance of LPS, mitigating emissions from LPS would become even more important in future. However, Indian GHG and local pollutant emission trajectories have a disjoint in future as SO_2 emissions decline due to deeper penetration of FGD in power sector, improved fuel quality resulting in lower sulfur and ash contents, stricter enforcement of emission regulations and efficiency improvements. Although GHG and local pollutant emission mitigation targets for a country are often useful as overall policy targets, the marginal mitigation cost for achieving each target varies across regions and sectors. The LPS analysis contributes to effectiveness of emissions mitigation by indicating the locations and sectors where controls can lead to maximum benefits. The present work is a step in this direction for India.

References

AIM Project Team (2002) AIM-Local: a user's guide. AIM interim paper, IP-02-01. National Institute for Environmental Studies, Tsukuba

Biswas D (ed) (1999) Parivesh news letter: June 1999. Central Pollution Control Board, Ministry of Environment and Forests, Government of India, New Delhi

CEA (Central Electricity Authority of India) (1996) Performance review of thermal power stations 1995-96. New Delhi

CMIE (1999) India’s energy sector. Center for Monitoring Indian Economy, Mumbai

CMIE (2002a) India’s Energy Sector. Center for Monitoring Indian Economy, Mumbai

CMIE (2002b) Prowess: the Indian corporate database. Center for Monitoring Indian Economy, Mumbai

Garg A (2000) Technologies, policies and measures for energy and environment future. Doctoral thesis, Indian Institute of Management, Ahmedabad

Garg A, Shukla PR, Bhattacharya S, Dadhwal VK (2001a) Sub-region (district) and sector level SO_2 and NO_X emissions for India: assessment of inventories and mitigation flexibility. Atmospheric Environment 35: 703-713

Garg A, Bhattacharya S, Shukla PR, Dadhwal VK (2001b) Regional and sectoral assessment of greenhouse gas emissions in India. Atmospheric Environment 35: 2679-2695

Garg A, Ghosh D, Shukla PR (2001c) Integrated energy and environment modelling and analysis for India. OPSEARCH of India 38

Garg A, Kapshe M, Shukla PR, Ghosh D (2002) Large point source (LPS) emissions from India: regional and sectoral analysis. Atmospheric Environment 36: 213-224

Garg A, Shukla PR (2002) Emissions inventory of India. Tata McGraw-Hill Publishing Company Ltd., New Delhi

Hu X, Yang H (2000) Disaggregate SO_2 emissions from national total to county level distributions for China. 5th AIM international workshop, National Institute of Environmental Studies, Tsukuba

IPCC (1996) Revised IPCC guidelines for national greenhouse gas inventories: reference manual, vol 3. Inter Governmental Panel on Climate Change, Bracknell

IPCC (2000) Special report on emissions scenarios. Cambridge University Press, Cambridge

Kainuma M, Matsuoka Y, Morita T, Hibino G (1999) Development of an end-use model for analyzing policy options to reduce greenhouse gas emissions. IEEE trans on systems, man, and cybernetics- part C: Applications and reviews 29-3: 317-324

Kainuma M, Matsuoka Y, Morita T (2001) CO_2 emission forecast in Japan by AIM/end-use model. OPSEARCH of India 38-1: 110-125

Kuznets SS (1958) Six lectures on economic growth. Free Press New York, New York

Li YF, Zhang YJ, Cao GL, Liu JH, Barrie LA (1999) Distribution of seasonal SO_2 emission from fuel combustion and industrial activities in Shanxi province, China, with $1/6^o x 1/4^o$ longitude/latitude resolution. Atmospheric Environment 33: 257-265

Mashelkar RA, Biswas DK, Krishnan NR, Mathur OP, Natarajan R, Niyati KP, Shukla PR, Singh DV, Singhal S (2002) Report of the expert committee on auto fuel policy. Ministry of Petroleum and Natural Gas, Government of India, New Delhi

Shukla PR, Ghosh D, Chandler W, Logan J (1999) Developing countries and global climate change: electric power option in India. PEW Center on Global Climate Change, Arlington

UN (United Nations) (1998) World population projections to 2150. United Nations Department of Economic and Social Affairs Population Division, New York

WB (World Bank) (1997) A planner's guide for selecting clean coal technologies for power plants. World Bank Technical Paper No 387, The World Bank, Washington, D.C.

Appendix: AIM/Local Modeling Approach

The AIM/Local model, suitable for estimating future emissions from large point sources and area sources, is demand driven. The model uses linear programming approach to arrive at the optimal combination of technologies with least cost to satisfy the service demand while meeting the environmental targets and / or energy supply constraints in a specific region. It calculates emissions from LPS and area sources separately. The total emissions from a region are then obtained by summing up the LPS and area source emissions.

Emissions from large point sources (LPS)

The calculation of emissions from energy combustion may be done at three different levels referred to as tiers 1, 2 and 3 in the IPCC Guidelines (IPCC 1996). Tier-1 methodology, concentrates on estimating the emissions from the carbon content of energy kind supplied to the country as a whole or to the main energy combustion activities. This is a simple method and emissions from all sources of combustion are estimated on the basis of the quantities of energy kind consumed and average emission factors. Tier-2 estimation methodology is based on detailed energy/technology information covering stationary and mobile sources. It is more detailed than tier-1 methodology but uses the same concept of energy kind consumption based emission coefficients like CO_2 emissions per unit of coal combustion. Tier-3 is similar to tier-2 except that the emission coefficients are based on enduse demands like CO_2 emissions per unit of power generated. AIM/Local model uses a combination of tier-2 and 3 methodology of emission estimation. LPS emissions in the model are estimated by two different approaches. Model follows an approach similar to tier-2 for the estimates of emissions from the LPS for energy consumption. The data required includes information about the production quantity, production process, energy combustion by various technologies, emission coefficients for the energy kind and pollution removal technologies used. The emissions are estimated by multiplying the energy consumption by each technology with respective emission coefficients for that energy kind.

In this model, tier-3 approach is used for estimation of emissions from the industrial processes. The data requirement for this approach includes production quantity, production process and emissions factors per unit of production. Emissions are estimated by multiplying the production quantity by the corresponding emission coefficients.

Net emissions from an LPS in both the above approaches are calculated by accounting for the pollution removal factor due to the pollution removal technology.

Thus emissions from LPS for energy consumption and production processes are given by

$$Q_l^{LPS} = R_l^{LPS} \times \{\sum_k (E_{l,k}^{LPS} \times f_k) + \sum_v (V_{l,v}^{LPS} \times f_v)\} \quad (1)$$

Where,

Q_l^{LPS} : Net emission from large point source l

R_l^{LPS} : Release rate of pollutants after removal technology of large point source l

$E_{l,k}^{LPS}$: Energy consumption of energy kind k for large point source l

f_k : Emission coefficient of energy kind k

$V_{l,v}^{LPS}$: Production quantity of production process v for large point source l

f_v : Emission coefficient of production process v

k : Energy kind

v : Production process

Emissions from area sources (AS)

In the present study the start year of modeling has been taken as 1995. India had 25 States and 6 Union territories in 1995. These are further subdivided in 466 small administrative areas called districts. Due to reorganization of states and subdivision of districts, this number has changed over the years but for the modeling purpose administrative boundaries as of 1995 have been used. Information collection on the district level for all the required parameters is difficult due to limited data availability. AIM/Local model provides the flexibility of regional definition on two levels and facilitates estimation of aggregate emissions for a larger region and allocation of the same to the smaller areas of the region based on suitable allocation index for each sector.

In this model, an approach similar to the tier-2 method has been used for emission estimates from area sources. The emissions for a sector are estimated by multiplying the consumption for each energy kind in a technology with respective emission coefficient for the energy kind and the production quantity for each production process with respective emission coefficient.

This can be given by the following equation:

$$Q_j^{AS} = \sum_k (E_{j,k}^{AS} \times f_{j,k}^{AS}) + \sum_v (V_{j,v}^{AS} \times f_{j,v}^{AS}) \tag{2}$$

$$E_{j,k}^{AS} = E_{j,k} - \sum_{l \in \{\text{point sources belong to sector } j\}} E_{l,k}^{LPS} \tag{3}$$

$$V_{j,v}^{AS} = V_{j,v} - \sum_{l \in \{\text{point sources belong to sector } j\}} V_{l,v}^{LPS} \tag{4}$$

Where,

Q_j^{AS} : Emissions from sector j from area sources

$f^{AS}_{j,k}$: Emission coefficient of energy kind k from sector j, taking into account the effect of removal technologies

$E^{AS}_{j,k}$: Energy consumption of energy kind k for sector j

$E_{j,k}$: Total energy consumption of energy kind k for sector j

$f^{AS}_{j,v}$: Emission coefficient of production process v from sector j, taking into account the effect of removal technologies

$V^{AS}_{j,v}$: Production quantity of production process v for sector j

$V_{j,k}$: Total production quantity of production process v for sector j

j : Sector

The sectoral emissions estimated on the national level are then allocated to the districts based on a suitable allocation index like district population, area, road density etc., for which the information is available on district level. Suitable parameters, which were considered as the major drivers for emissions from a particular sector, were used to generate this index. The emissions from district i can thus be given by

$$q_i^{AS} = \sum_j (Q_j^{AS} \times \frac{I_{i,j}}{\sum_i I_{i,j}}) \tag{5}$$

Where,

q_i^{AS} : Emission in district i from area sources

$I_{i,j}$: Emission intensity index for sector j in district i

Total emissions

Equation (1) gives the emissions from the point sources and equation (2) gives the emissions from a sector in a region. The total emissions from sector j in a region can thus be given by

$$Q_j = Q_j^{AS} + \sum_{l \in \{\text{point sources belong to sector } j\}} Q_l^{LPS} \tag{6}$$

The total emissions at the district level can be calculated by summing up the allocated area source emissions and point source emissions from a district.

$$Q_i = q_i^{AS} + \sum_{l \in \{\text{point sources in district } i\}} Q_l^{LPS} \tag{7}$$