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Top-down Assessment of Air Pollution and GHGs for Dhaka, Bangladesh

Analysis of GAINS Derived Model Data

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Technical report

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Executive Summary

A combination of numerous local emissions sources in addition to special local and regional meteorological conditions gives Dhaka exceedingly high air pollution concentrations throughout the year, and especially during the winter season. The exposure of the cities estimated 12-15 million residents to this alarmingly poor air quality demands attention including immediate research and corresponding mitigation. Establishing emission inventories and conducting air pollution assessments are the first steps on the path to mitigating air quality problems.

The city of Dhaka was chosen for this assessment due to the current ongoing project Bangladesh Air Pollution Management (BAPMAN), which concentrates mostly on the capital city Dhaka. Through the BAPMAN project, a total bottom-up emissions inventory is currently being performed, and it is useful to the project to compare top-down emissions data results. The Greenhouse Gas and Air Pollution Interactions and Synergies model (GAINS) was used to perform this top-down assessment due to the model's integrated assessment approach of capturing interactions between air pollution control and economic development, as well as its focus on presenting cost effective pollution control strategies.

Results from the GAINS model assessment for Dhaka shows that for 2010 the total $PM_{2.5}$ emissions were 35000 tons/year, and the total PM_{10} emissions were 45000 tons/year. The top sectors making up the PM emissions included Industry and Residential sectors, where the specific sub-sectors were brick/cement production and residential cooking respectively. The top fuels making up the emissions were "no fuel use" and "fuelwood direct". GAINS estimates that the top 3 technical control measures available for PM can eliminate approximately 1/3 of the PM emissions at a cost of .65 MEuro/year.

GAINS results also show that for Dhaka in 2010 the total SO_2 emissions were 34000 tons/year, dominated by the Industrial sector, made up of the sub-sectors of new power plants and industrial combustion, using hard coal and natural gas fuels. NO_X emissions for Dhaka in 2010 were 30000 tons/year, dominated by the Industrial (combustion/power plants) and Transport sectors. The fuels used by these two sectors include natural gas, gasoline, and medium distillates (eg. diesel). GHG emissions for Dhaka in 2010 exceeded 23 million tons/year CO_2 equivalent, dominated by the Industrial (combustion/power plants) and Agricultural sectors. The fuels used by these two sectors include natural gas and hard coal. No mitigation controls/costs were available for SO_2, NO_X, and GHGs in the model.

GAINS can be seen a useful "screening-type study" tool for emissions, especially for developing countries such as Bangladesh due to a lack of available compiled data. The GAINS approach can be seen as a simplified generalization tool to be used to pin point pollutants and related sources which deem closer research and analysis using more specific tools or ground-based monitoring. This report has provided this valuable data, and will be helpful in completing the ongoing bottom-up emission inventory for Dhaka within the BAPMAN project. Unfortunately though without the inclusion of GHG controls/costs in the model, it is not possible to begin co-benefit/co-control analysis. However, it should be considered to perform an assessment using GAINS at the beginning of each international emission inventory related project in order to establish a general baseline and screening analysis of top-down emissions data for the city/area of interest.

Top-down Assessment of Air Pollution and GHGs for Dhaka, Bangladesh

Analysis of GAINS Derived Model Data

1 Introduction

Dhaka can be considered the mega-city with the world's worst urban air quality (Gurjar et al., 2008). A combination of numerous local emissions sources in addition to special local and regional winter meteorological conditions gives the city exceedingly high air pollution concentrations throughout the year, and especially during the winter season (Randall et al., 2011). The exposure of the cities estimated 12-15 million residents to this alarmingly poor air quality demands attention including immediate research and corresponding mitigation. The World Health Organization (WHO) estimates that up to 10,000 pre-mature deaths are associated with outdoor air pollution annually in Bangladesh (WHO, 2009).

Urban air pollutant emissions plus GHG emissions will be analyzed for Dhaka to determine past and projected trends in emissions rates, for the main activities within the main sectors responsible for the bulk of the emissions for each pollutant investigated. This information is necessary to examine the various co-controls available in order for the maximum co-benefit to society and the global climate. Such a complex problem requires an integrated approach; and *integrated assessment modelling* is an excellent tool to provide data for this purpose.

The *Greenhouse Gas and Air Pollution Interactions and Synergies* model (GAINS) developed at the International Institute for Applied Systems Analysis (IIASA) was selected as the most appropriate tool to perform this analysis of integrated assessment data for Dhaka. As stated by IIASA, the purpose of the GAINS model is to:

> •*To capture interactions between pollution control and economic development; and*
> •*To identify cost-effective pollution-control strategies that put the least burden on economic development. It is this special focus on the implications for economic policies of controlling air pollution and mitigating greenhouse gases, and vice versa, advanced methodologies to systematically identify pollution control strategies that put least cost to the economy while maximizing a wide range of environmental benefits.* (IIASA, 2008)

The GAINS model targets common air pollutants as well as GHGs, where these are based on underlying air quality policy targets (Figure 1). GAINS is based on the premise that there distinct and important linkages between air pollution emissions and GHGs due to common sources and co-benefits through co-control measures.

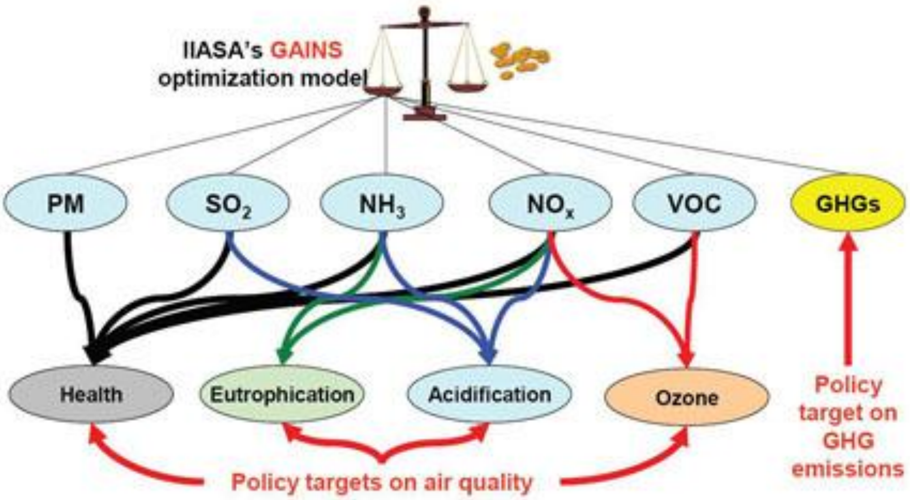


Figure 1: Diagram of the GAINS model underlying framework (Source: IIASA).

Using the GAINS model, the following air pollution components will be examined for Dhaka:

- $PM_{2.5}$
- PM_{10}
- SO_2
- NO_x
- GHGs

For each examined component the following information will be analyzed:

- Emissions (2010) and decadal trends
- Activity (fuel) distributions of emissions (2010) and decadal trends
- Sector distributions of emissions (2010) and decadal trends
- Sub-sector distributions of emissions (2010)
- Sub-sectors contributing to the activities with the greatest emissions (2010)
- Mitigation control options and related removal efficiency (only available for PM)
- Mitigation control costs (only available for PM)

The top-down approach employed by GAINS can be seen as a valuable screening-type tool for cities like Dhaka which have little available air pollution data and related source information compiled. The approach can be seen as a simplified generalization tool to be used to pin point pollutants and related sources which deem closer research and analysis using more specific tools or ground-based monitoring. The following schematic (Figure 2) illustrates the information to be examined for Dhaka and the related data flow:

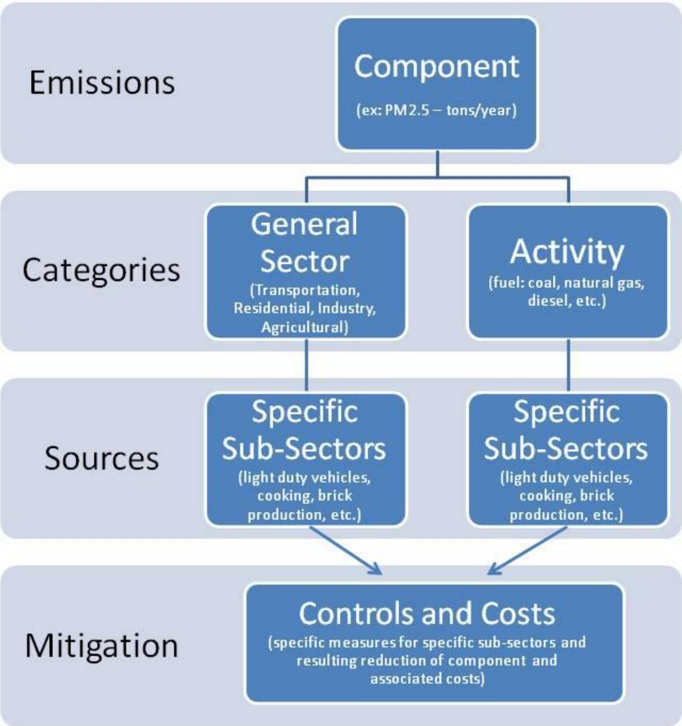


Figure 2: Schematic of information collected and model flow.

2 Methods

The city of Dhaka was selected for this integrated assessment due to the need for relevant data/analysis (and data comparisons) for the Bangladesh Air Pollution Management (BAPMAN) project in which Dhaka is of primary focus.[1]

Part I of the GAINS user handbook guidelines (IIASA, 2009) were followed in order to properly access the online data and navigate the interface. Registration was necessary to obtain access to all of the GAINS models.

The GAINS South Asia model[2] was used to collect emissions data and related control information for Dhaka, Bangladesh. The default scenario "Final Report: Baseline08" (last updated September 2008) was used in this analysis, which is the baseline scenario developed on the basis of the results from the EU funded *GAINS-Asia project* (IIASA, 2008), which also includes implementation of all current legislation through 2008.

An offline excel database was created from the exported GAINS data collected in order to complete the thorough analysis. Data was copy and pasted from GAINS outputs into Excel, where analysis was conducted there. It should be noted that no additional resources other than the GAINS South Asia model were used for raw data collection in this report.

[1] More information can be found regarding the BAPMAN project at: http://bapman.nilu.no
[2] Model is found here: http://gains.iiasa.ac.at/gains/IND/index.login?logout=1

3 Results

The air pollution emissions components used for this analysis of Dhaka includes: $PM_{2.5}$, PM_{10}, SO_2, NO_X, and GHGs (which includes CO_2, CH_4, N_2O, and FGAS[3]).[4] A general picture of the total top-down emissions data (non-GHGs) for Dhaka (Figure 3) shows the expected total emissions increase of all components over the decades through 2030, where SO_2 is increasing at a greater rate than the other components and is expected to exceed 110000 tons/year in 2030. A similar picture can be seen for GHG emissions (Figure 4), where CO_2 emissions are increasing at a high rate and CO_2 alone is projected to exceed 30 million tons/year in 2030.

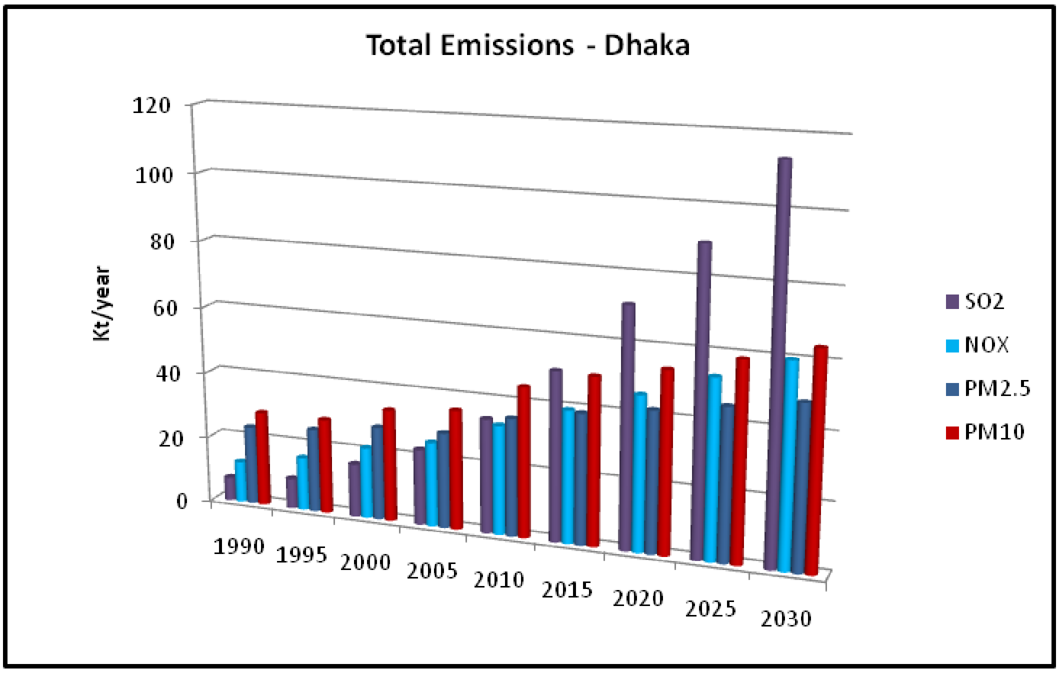


Figure 3: Total non-GHG emissions for Dhaka from 1990-2030.

[3] The three F gasses are: HFC, PFC, and SF_6
[4] GAINS model also includes the following components for Dhaka: VOCs, NH3, N2O, and CH4 – these components were not included in this study.

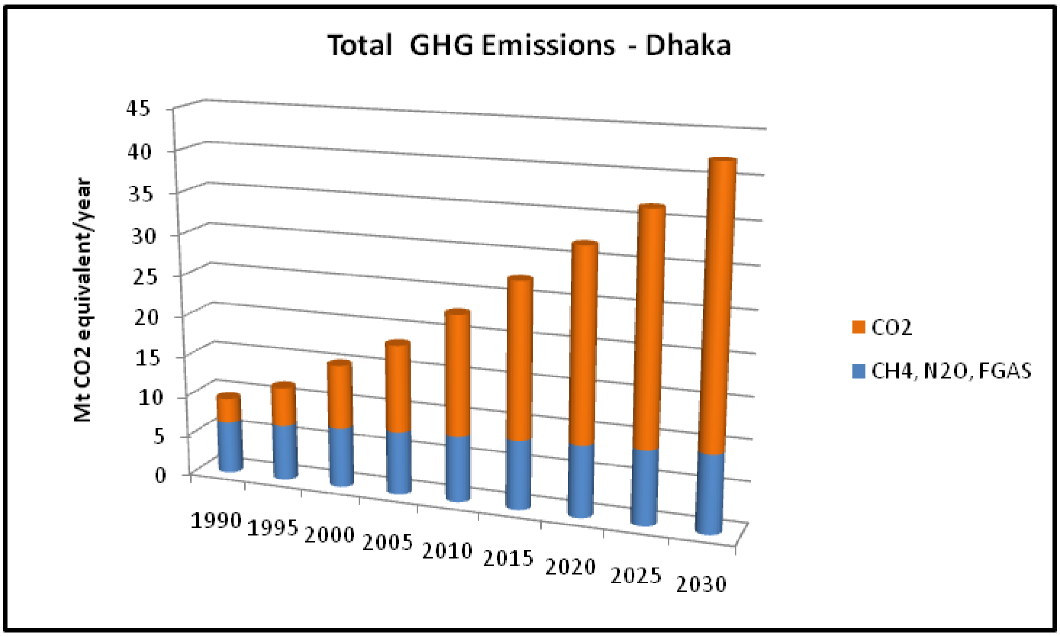


Figure 4: Total GHG emissions for Dhaka from 1990-2030.

Each individual component presented above will be specifically analyzed in the following sections to identify the sources of the emissions (sectors and activities), as well as the effect of controls and the related costs (for PM only) – primarily for the nearest year available in the model, 2010.

3.1 $PM_{2.5}$

$PM_{2.5}$ emissions for Dhaka are modeled to reach 48000 tons/year in 2030, where the current level for 2010 is modeled at approximately 35000 tons (Figure 5). These $PM_{2.5}$ emission will be analyzed for the particular activity levels, sector levels, and sector emissions from specific activities making up these total emission values. Control options and associated costs will also be presented.

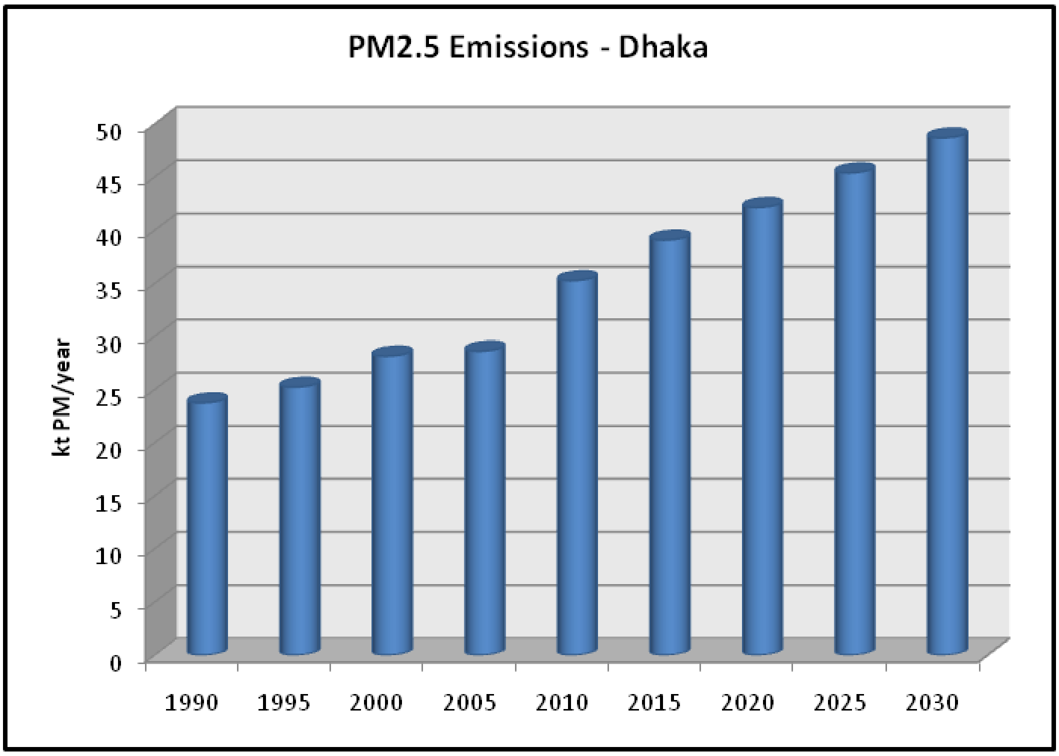


Figure 5: $PM_{2.5}$ Emissions for Dhaka, 1990-2030.

3.1.1 Activity

The $PM_{2.5}$ emissions (as shown in Figure 5) can be broken down into specific activities (source fuel types) as presented in Figure 6. The "no fuel use"[5] activity represents the greatest contribution of $PM_{2.5}$ emissions which is greatly increasing over time, exceeding 35000 tons/year PM in 2030. The second largest contribution of $PM_{2.5}$ emissions comes from the "fuelwood direct" activity, which is gradually decreasing over time, estimated to be closer to 5000 tons/year in 2030. The other activities associated with $PM_{2.5}$ emissions have minimal emission contributions in comparison to the previous two activities mentioned; for example the "Gasoline and other light fractions of oil" and "Medium distillates (diesel, light fuel oil)" activities never contribute for more than 1000 tons $PM_{2.5}$ emissions for a given year.

[5] "no fuel use" activity is the sum of the emissions from all sectors that do not come from fuel combustion.

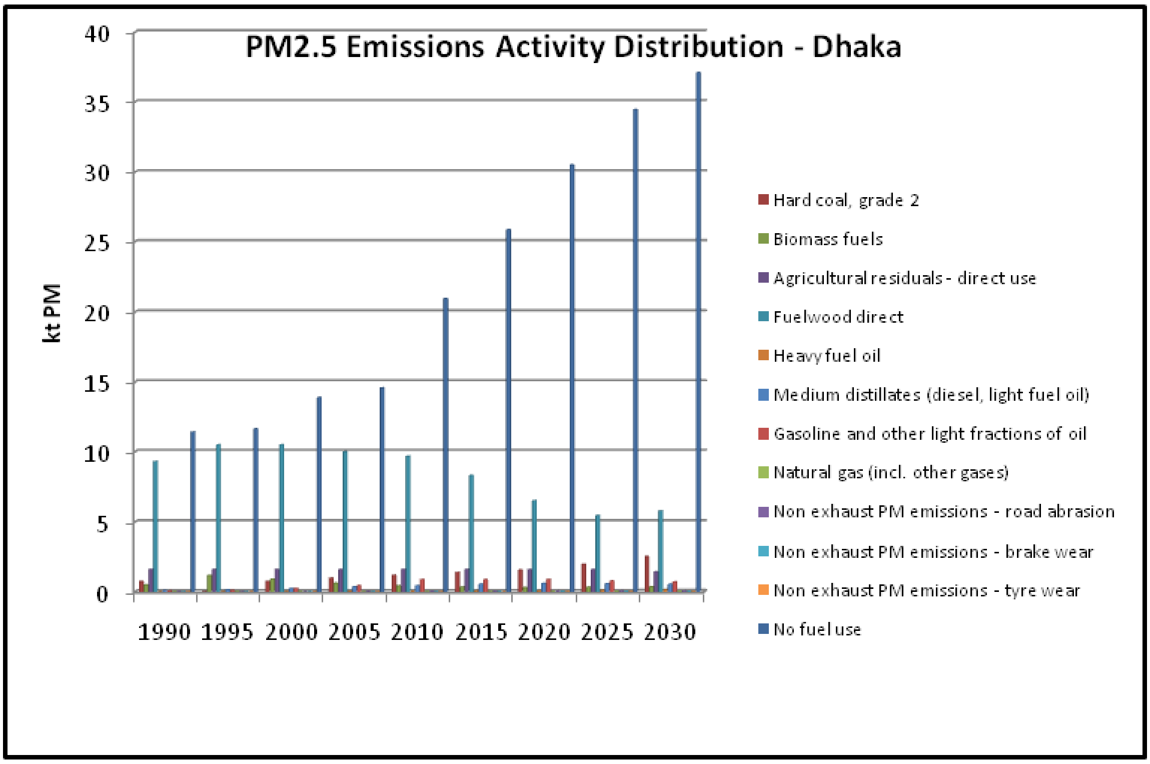


Figure 6: $PM_{2.5}$ Emissions Activity Distribution for Dhaka from 1990-2030.

The modeled situation for the associated activities for $PM_{2.5}$ emissions for 2010 (Figure 7) show that the “no fuel use” activity represents approximately twice as much of the PM emissions as the “fuelwood direct” activity for that year.

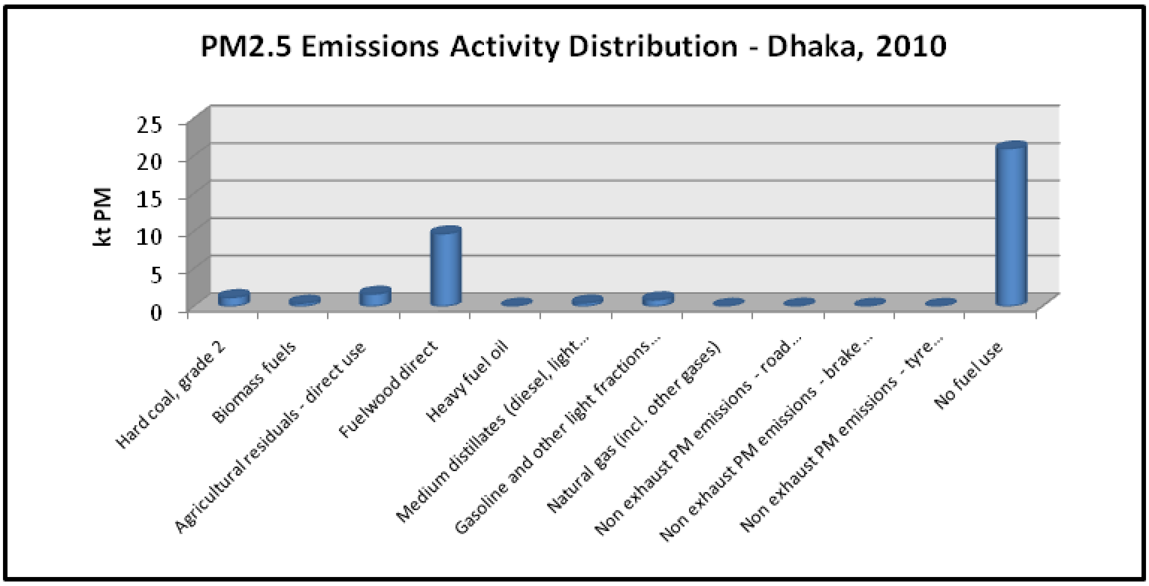


Figure 7: $PM_{2.5}$ Emissions Activity Distribution for Dhaka for 2010.

3.1.2 Sector

The $PM_{2.5}$ emissions can be broken down in to *general* sectors as presented in Figure 8, which shows a gradual decrease over time of $PM_{2.5}$ emissions coming from the residential sector and a steady increase from the industrial sector. Here the transport sector displays a low contribution of $PM_{2.5}$ emissions, emitting under 2000 tons/year. A graph displaying the *specific* sector distributions of $PM_{2.5}$ emissions from 1990-2030 is in Appendix A.

The *specific* sector distribution for 2010 (Figure 9) shows that a majority of $PM_{2.5}$ emissions comes from the brick production industry, approximately 15000 tons. Residential cooking stoves also show a large contribution for 2010 at 11000 tons, making up almost 10 times the $PM_{2.5}$ contribution compared to the transport related specific sectors (1300 tons).

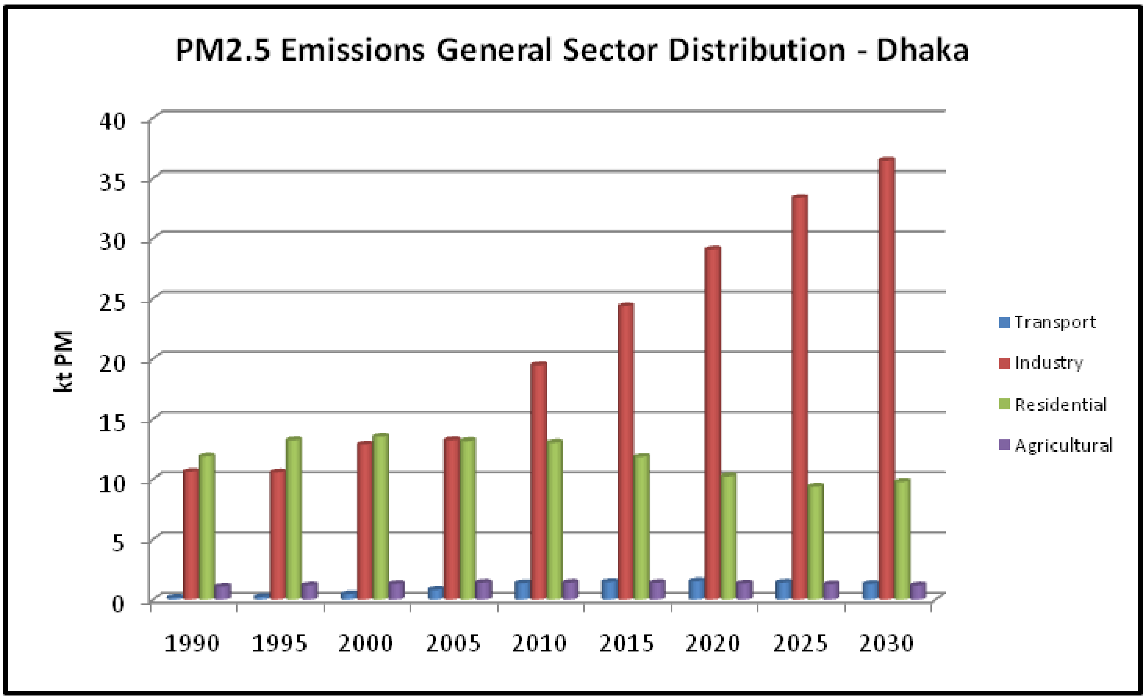


Figure 8: $PM_{2.5}$ Emissions General Sector Distribution for Dhaka from 1990-2030.

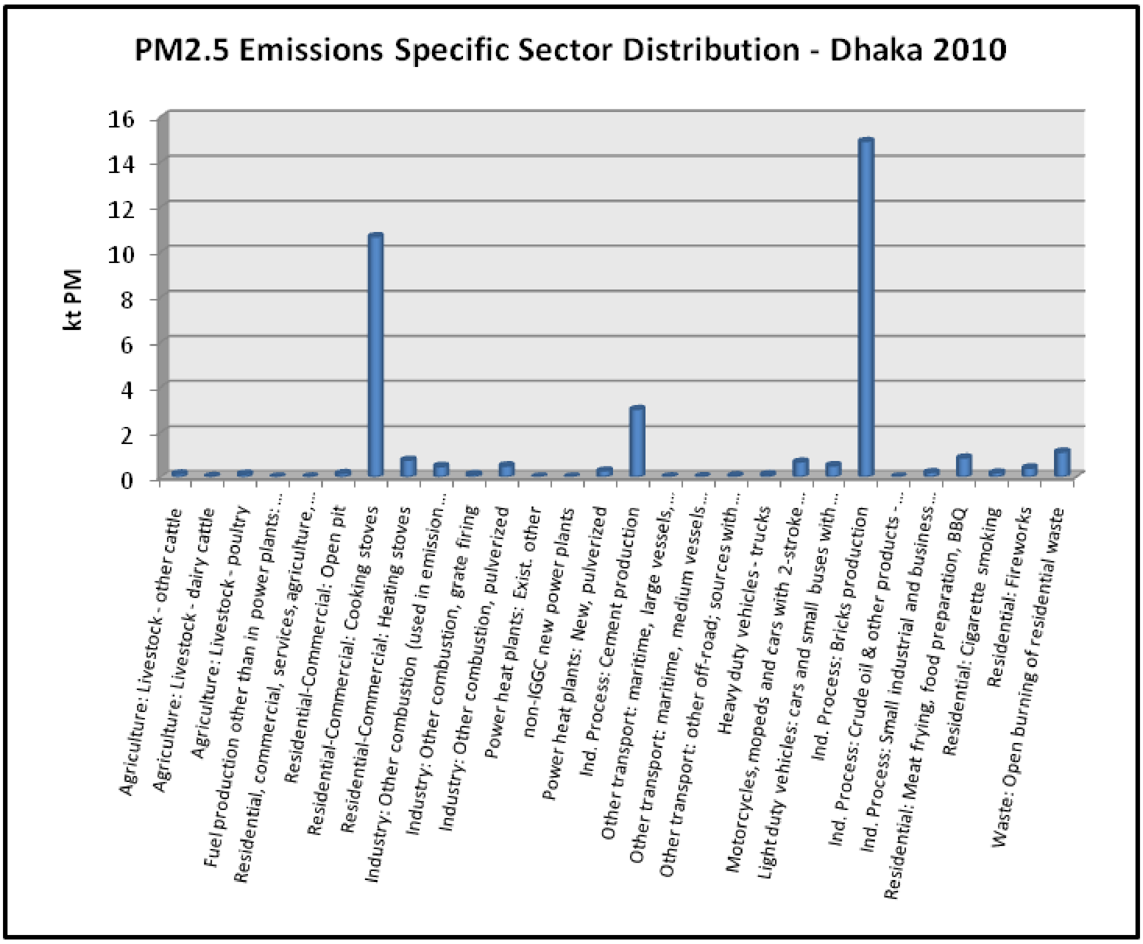


Figure 9: PM$_{2.5}$ Emissions Specific Sector Distribution for Dhaka for 2010.

3.1.3 Sector-Activity

Figure 7 shows that the activity "no fuel use" (emissions not due to fuel combustion) has the greatest contribution to PM$_{2.5}$ emissions in 2010, over 20000 tons PM$_{2.5}$. The specific sectors which make up this activity contribution can be seen in Figure 10, where brick production is the major source for this activity type (15000 tons), followed by cement production (3000 tons).

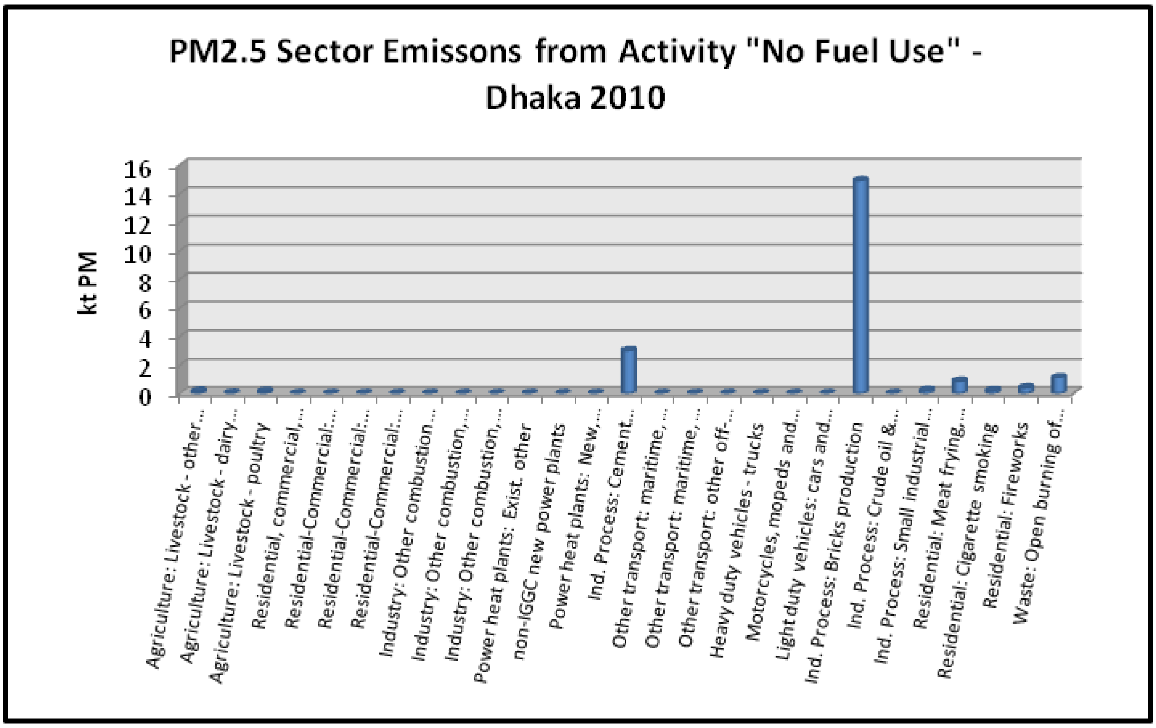


Figure 10: $PM_{2.5}$ Sector Emission from Activity "No Fuel Use" in Dhaka for 2010.

Figure 7 also shows that the activity "fuelwood direct" has a large contribution of $PM_{2.5}$ emissions in 2010, approximately 9000 tons $PM_{2.5}$. The specific sectors which make up this activity contribution can be seen in Figure 11, where residential cooking stoves is the major source for this activity type at approximately 8500 tons.

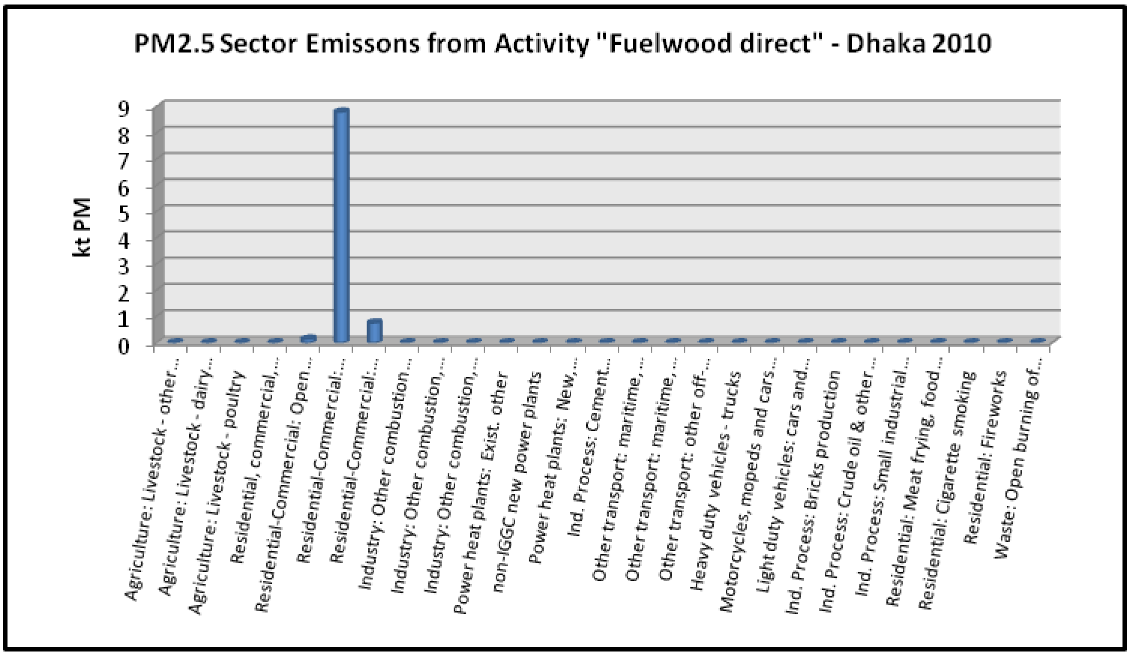


Figure 11: $PM_{2.5}$ Sector Emissions from Activity "Fuelwood direct" for Dhaka in 2010.

3.1.4 Controls

21 specific mitigation/controls for $PM_{2.5}$ were available and the results of these control options in regards to no-control options are shown in Figure 12 an explanation of the abbreviations of the controls can be found in Appendix B.

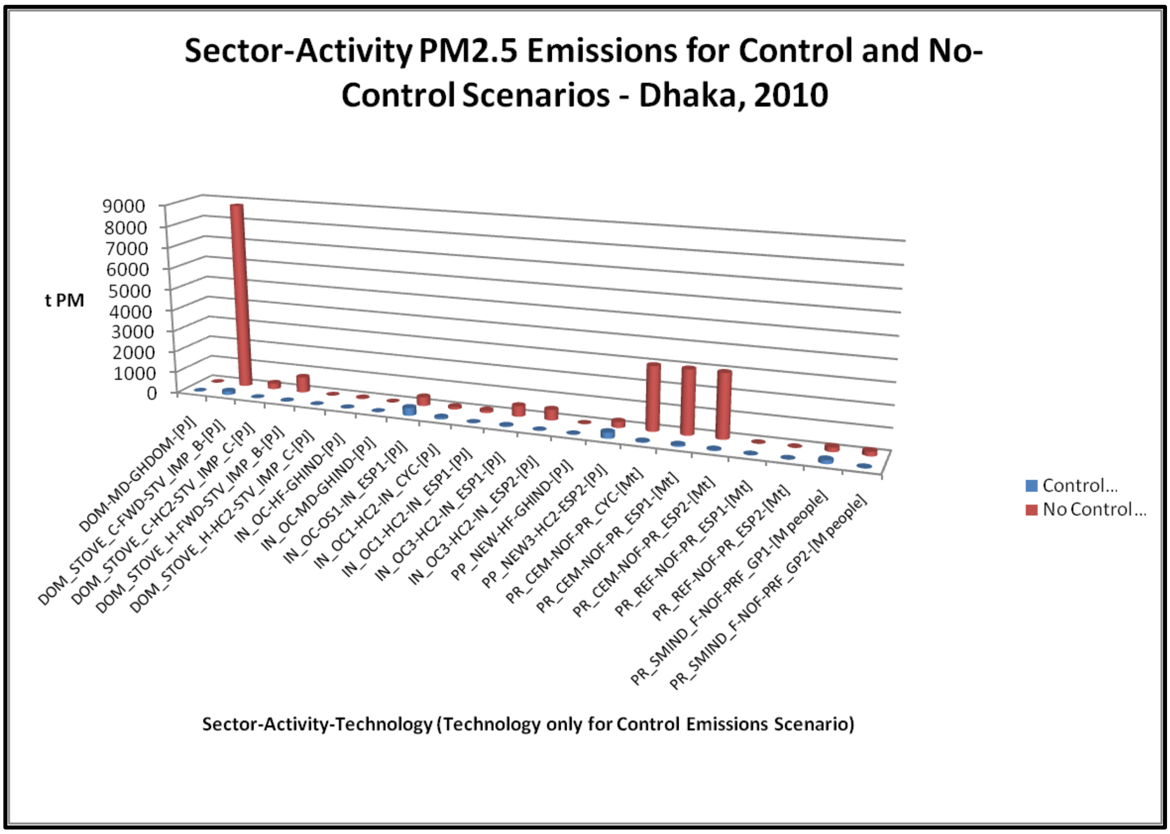


Figure 12: Sector-Activity $PM_{2.5}$ Emissions for Control and No-control Scenarios in Dhaka for 2010.

A list of the top 10 controls and their $PM_{2.5}$ removal efficiency can be seen in Table 1. The chosen control options are applicable to the Industry (industrial process and industry) and Residential sectors. No controls were available for the Transport or Agricultural sector for this particular analysis. Implementation of the top three controls listed in Table 1 (control #1, 6, and 7 - one control for each sector)[6] can reduce the $PM_{2.5}$ emissions for year 2010 by approximately 12000 tons/year. This is more than 1/3 of the total $PM_{2.5}$ emissions for that year.

[6] Some of the controls cannot be combined because they are not complimentary.

Table 1: Top 10 $PM_{2.5}$ Control options and their emissions removal efficiency in Dhaka for the year 2010.

Control Measure		Total $PM_{2.5}$ emissions		
Name	Abbr	with Control (tons/yr)	without Control (tons/yr)	Difference (tons/yr)
1. Residential-Commercial: Cooking stoves-Fuelwood direct-Biomass stove improved-[10^15 Joules]	DOM_STOVE_C-FWD-STV_IMP_B-[PJ]	167.96	8792.86	8624.90
2. Residential-Commercial: Cooking stoves-Hard coal, grade 2-Coal stove improved -[10^15 Joules]	DOM_STOVE_C-HC2-STV_IMP_C-[PJ]	9.88	278.01	268.13
3. Residential-Commercial: Heating stoves-Fuelwood direct-Biomass stove improved-[10^15 Joules]	DOM_STOVE_H-FWD-STV_IMP_B-[PJ]	14.14	740.45	726.31
4. Industry: Other combustion, grate firing-Hard coal, grade 2-Electrostatic precipitator: 1 field - industrial combustion-[10^15 Joules]	IN_OC1-HC2-IN_ESP1-[PJ]	1.15	114.49	113.34
5. Industry: Other combustion, pulverized-Hard coal, grade 2-Electrostatic precipitator: 1 field - industrial combustion-[10^15 Joules]	IN_OC3-HC2-IN_ESP1-[PJ]	39.42	494.49	455.07
6. Industry: Other combustion, pulverized-Hard coal, grade 2-Electrostatic precipitator: 2 fields - industrial combustion-[10^15 Joules]	IN_OC3-HC2-IN_ESP2-[PJ]	4.51	494.49	489.98
7. Ind. Process: Cement production-No fuel use-Cyclone - - industrial process-[Mt]	PR_CEM-NOF-PR_CYC-[Mt]	33.92	2999.34	2965.42
8. Ind. Process: Cement production-No fuel use-Electrostatic precipitator: 1 field - industrial processes-[Mt]	PR_CEM-NOF-PR_ESP1-[Mt]	67.84	2999.34	2931.50
9. Ind. Process: Cement production-No fuel use-Electrostatic precipitator: 2 fields - industrial processes-[Mt]	PR_CEM-NOF-PR_ESP2-[Mt]	38.76	2999.34	2960.58
10. Ind. Process: Small industrial and business facilities - fugitive-No fuel use-Good practice: ind.process - stage 2 (fugitive)-[M people]	PR_SMIND_F-NOF-PRF_GP2-[M people]	6.84	205.17	198.33

3.1.5 Costs

Costs were determined for each of the 21 control options for PM emissions and are presented in Figure 13.

Table 2 presents the costs of the top $PM_{2.5}$ control options listed in Table 1. Costs range from less than 1 Euro up to over 16000 Euros/ton of reduced $PM_{2.5}$ emission. The implementation of top control measures #1, 6, and 7 would cost a total of 650000 Euros/year to save 12000 tons $PM_{2.5}$ emissions/year (1/3 of the total annual $PM_{2.5}$ emissions for 2010).

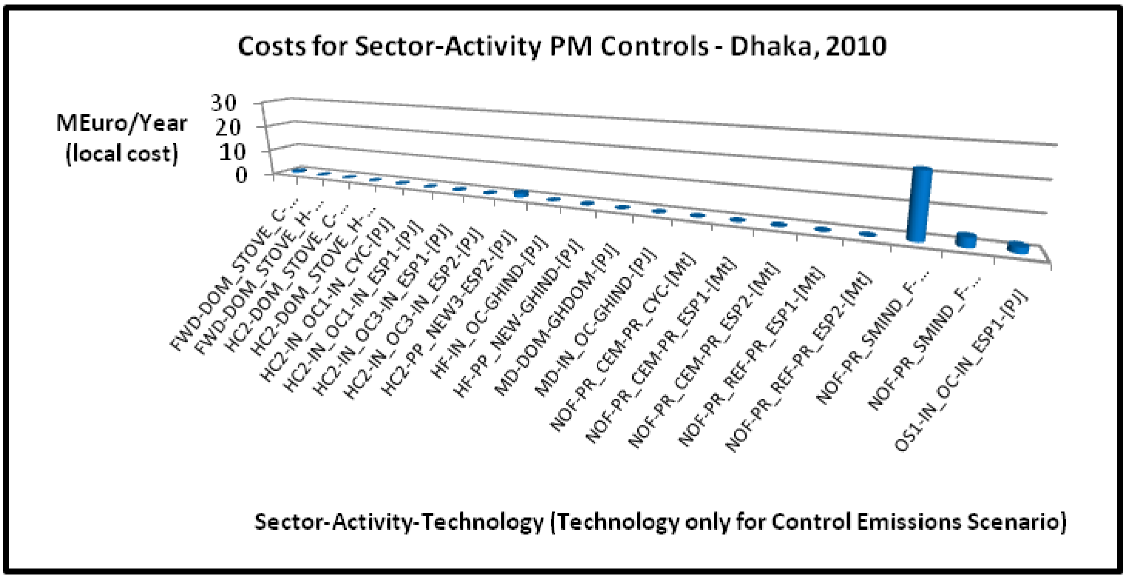


Figure 13: Costs of Sector-Activity $PM_{2.5}$ Controls for Dhaka in 2010.

Table 2: Top 10 $PM_{2.5}$ emission control options and their related costs for Dhaka in the year 2010.

Control Measure	Abbr	Cost Meuro/year	tons $PM_{2.5}$ emission reduced	cost Euro/ton $PM_{2.5}$ emission reduced
1. Residential-Commercial: Cooking stoves-Fuelwood direct-Biomass stove improved-[10^15 Joules]	DOM_STOVE_C-FWD-STV_IMP_B-[PJ]	0.6170	8624.9	71.54
2. Residential-Commercial: Cooking stoves-Hard coal, grade 2-Coal stove improved -[10^15 Joules]	DOM_STOVE_C-HC2-STV_IMP_C-[PJ]	0.0178	268.13	66.39
3. Residential-Commercial: Heating stoves-Fuelwood direct-Biomass stove improved-[10^15 Joules]	DOM_STOVE_H-FWD-STV_IMP_B-[PJ]	0.0649	726.31	89.36
4. Industry: Other combustion, grate firing-Hard coal, grade 2-Electrostatic precipitator: 1 field - industrial combustion-[10^15 Joules]	IN_OC1-HC2-IN_ESP1-[PJ]	0.0089	113.34	78.52
5. Industry: Other combustion, pulverized-Hard coal, grade 2-Electrostatic precipitator: 1 field - industrial combustion-[10^15 Joules]	IN_OC3-HC2-IN_ESP1-[PJ]	0.1366	455.07	300.17
6. Industry: Other combustion, pulverized-Hard coal, grade 2-Electrostatic precipitator: 2 fields - industrial combustion-[10^15 Joules]	IN_OC3-HC2-IN_ESP2-[PJ]	0.0309	489.98	63.06
7. Ind. Process: Cement production-No fuel use-Cyclone - -industrial process-[Mt]	PR_CEM-NOF-PR_CYC-[Mt]	0.0008	2965.42	0.27
8. Ind. Process: Cement production-No fuel use-Electrostatic precipitator: 1 field - industrial processes-[Mt]	PR_CEM-NOF-PR_ESP1-[Mt]	0.0192	2931.5	6.55
9. Ind. Process: Cement production-No fuel use-Electrostatic precipitator: 2 fields - industrial processes-[Mt]	PR_CEM-NOF-PR_ESP2-[Mt]	0.0234	2960.58	7.90
10. Ind. Process: Small industrial and business facilities - fugitive-No fuel use-Good practice: ind.process - stage 2 (fugitive)-[M people]	PR_SMIND_F-NOF-PRF_GP2-[M people]	3.2304	198.33	16288.00

3.2 PM_{10}

PM_{10} emissions for Dhaka are modeled to reach 64000 tons/year in 2030, where the current level for 2010 is modeled at 45000 tons/year (Figure 14). These PM_{10} emissions will be analyzed for the particular activity levels, sector levels, and sector emissions from specific activities making up these total emission values. Control options and associated costs will also be presented.

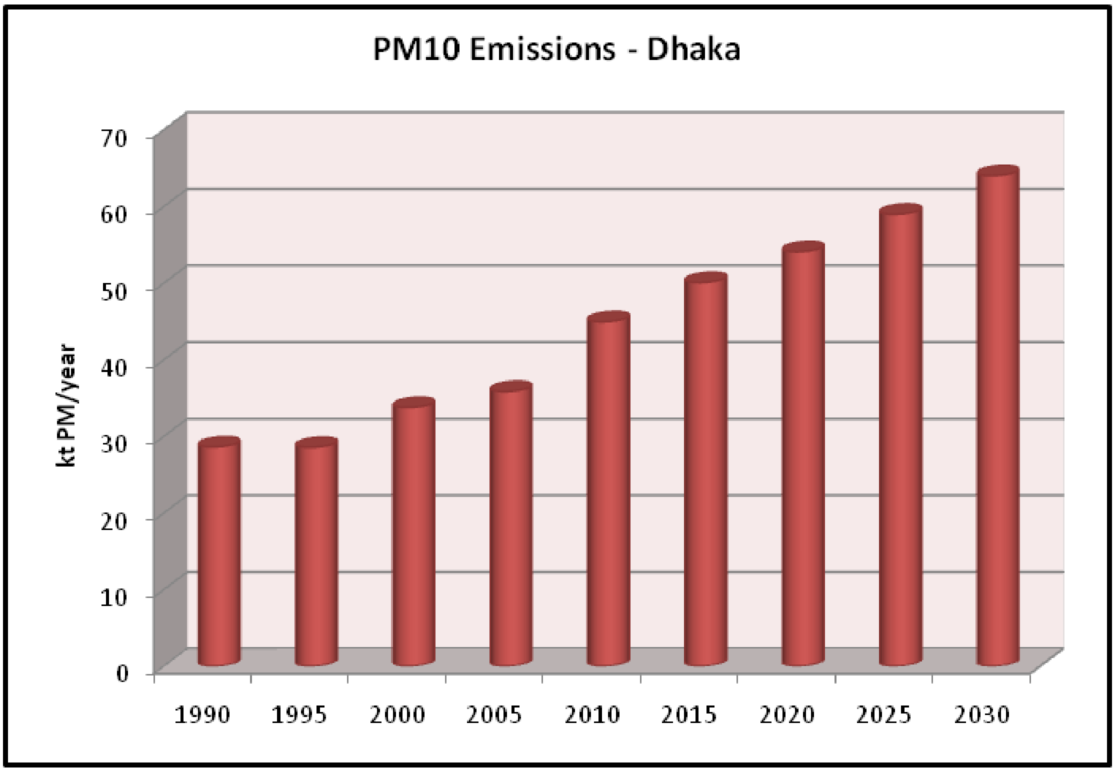


Figure 14: PM_{10} Emission for Dhaka, 1990-2030.

3.2.1 Activity

The PM_{10} emissions (as shown in Figure 14) can be broken down into specific activities (source fuel types) as presented in Figure 15. The “no fuel use” activity represents the greatest contribution of PM_{10} emissions which is greatly increasing over time, reaching 50000 tons/year in 2030. The second largest contribution of PM_{10} emissions comes from the “fuelwood direct” activity, which is gradually decreasing over time, estimated to be closer to 6000 tons in 2030. The other activities associated with PM_{10} emissions have minimal emission contributions in comparison to the previous two activities mentioned; for example the “Gasoline and other light fractions of oil” and “Medium distillates (diesel, light fuel oil)” activities never contribute for more than 1000 tons PM emissions for a given year.

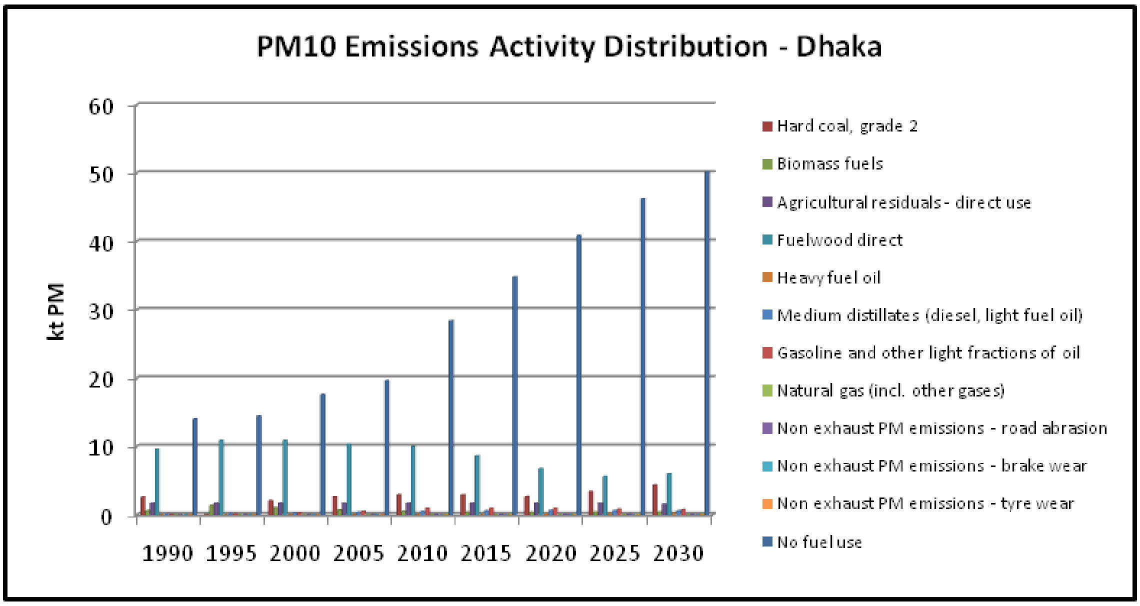


Figure 15: PM_{10} Emissions Activity Distribution for Dhaka from 1990-2030.

The modeled situation for the associated activities for PM_{10} emissions for 2010 (Figure 16) show that the "no fuel use" activity (emissions not due to fuel combustion) represents approximately twice as much of the PM_{10} emissions as the "fuelwood direct" activity for that year, with other activities at minimal levels.

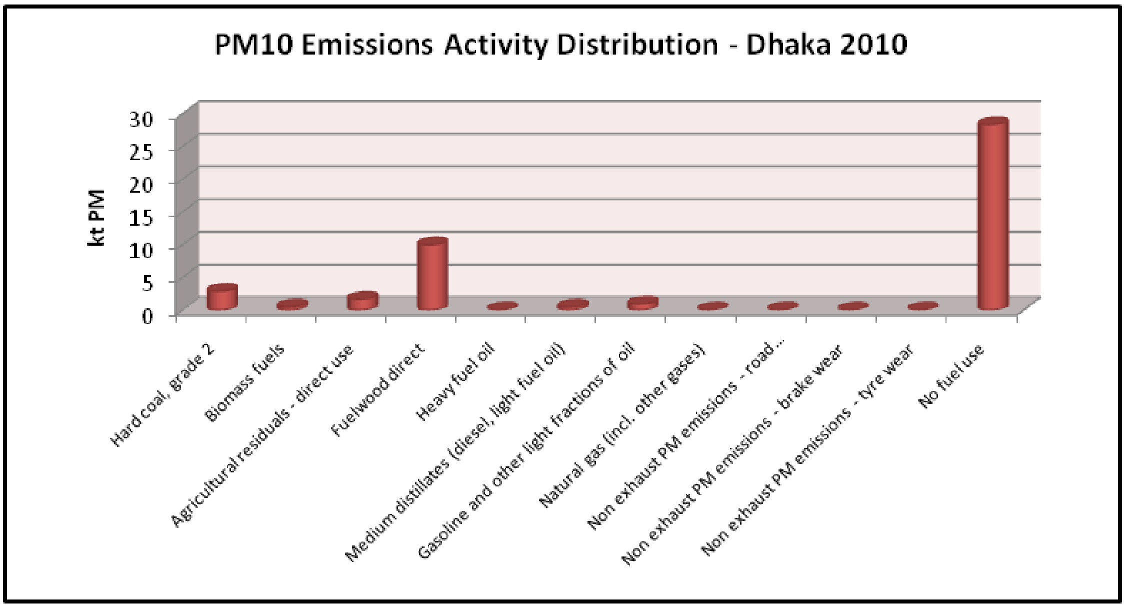


Figure 16: PM_{10} emissions activity distribution for Dhaka for 2010.

3.2.2 *Sector*

The PM_{10} emissions can be broken down in to *general* sectors as presented in Figure 17, which similarly to $PM_{2.5}$ shows a gradual decrease over time of PM_{10} emissions coming from the residential sector and a steady increase from the industrial sector. Here the transport sector also displays a low contribution of PM_{10} emissions, emitting under 2000 tons/year. A graph displaying the *specific* sector distributions of PM_{10} emissions from 1990-2030 is in Appendix B.

The *specific* sector distribution for 2010 (Figure 18) shows that a majority of PM_{10} emissions comes from the brick production industry, approximately 17000 tons. Residential cooking stoves also show a large contribution for 2010 at 11000 tons, making up almost 10 times the PM_{10} contribution compared to the transport related specific sectors (1500 tons).

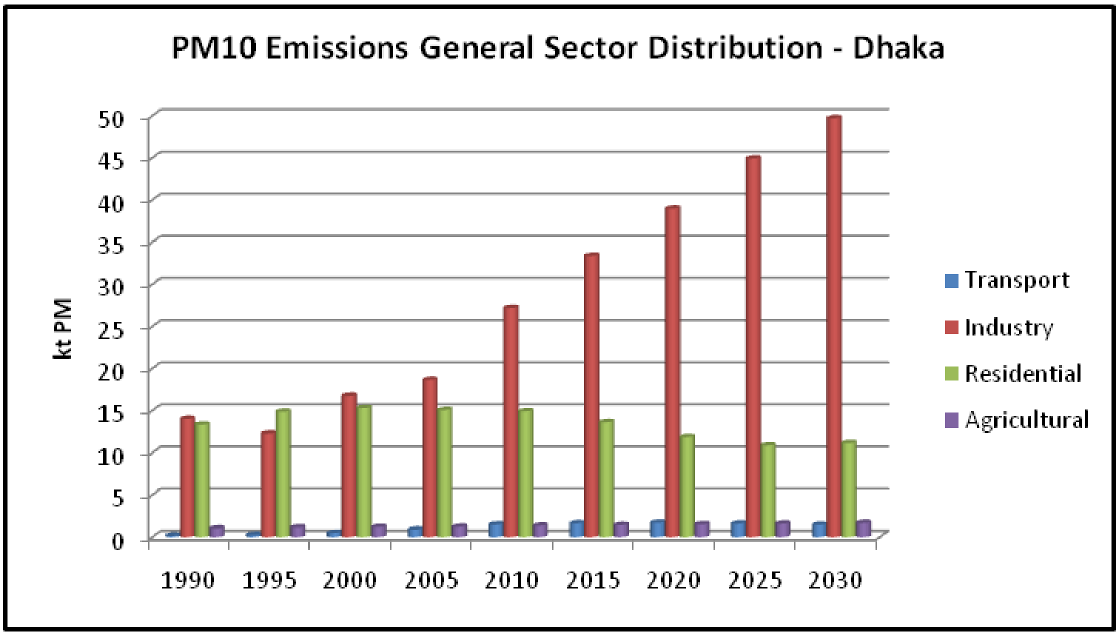


Figure 17: PM_{10} Emissions General Sector Distribution for Dhaka from 1990-2030.

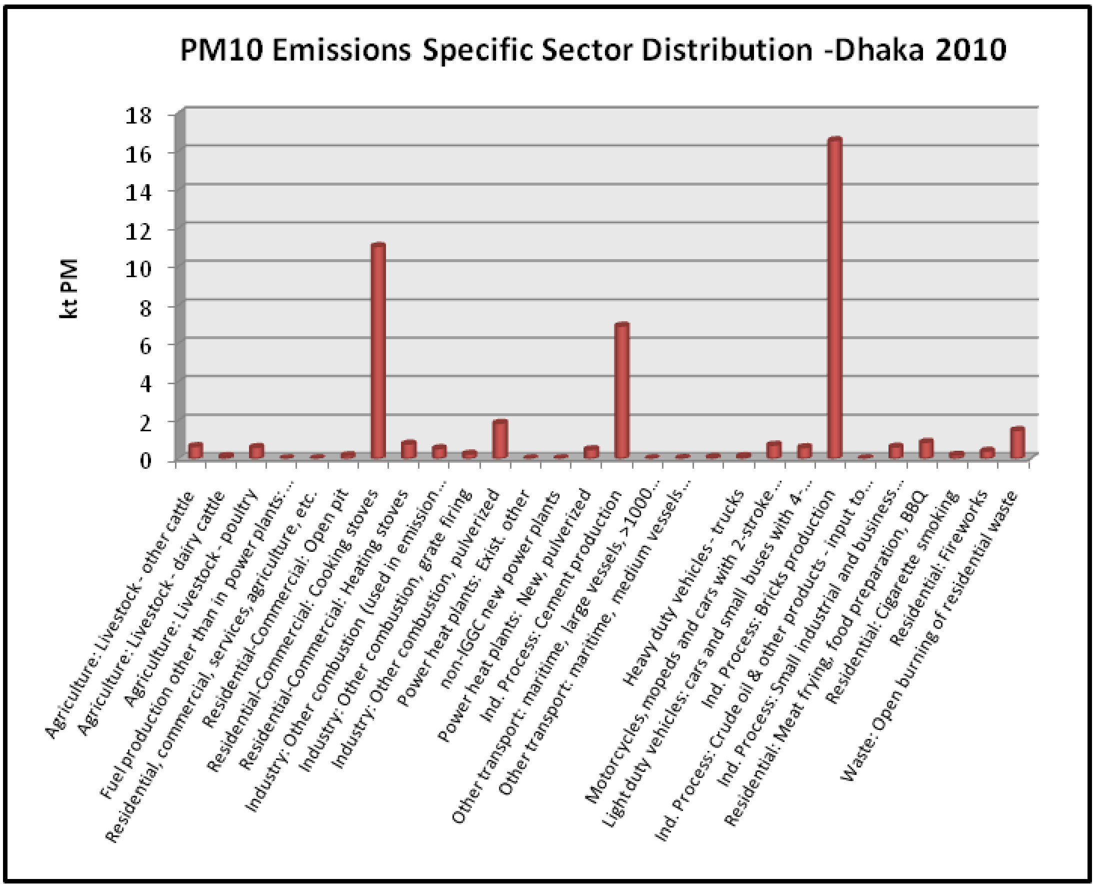


Figure 18: PM_{10} Emissions Specific Sector Distribution for Dhaka for 2010.

3.2.3 Sector-Activity

Figure 16 shows that the activity "no fuel use" (emissions not due to fuel combustion) has the greatest contribution of PM_{10} emissions in 2010, over 25000 tons PM/year. The specific sectors which make up this activity contribution can be seen in Figure 19, where brick production is the major source for this activity type (16000 tons/year), followed by cement production (7000 tons/year).

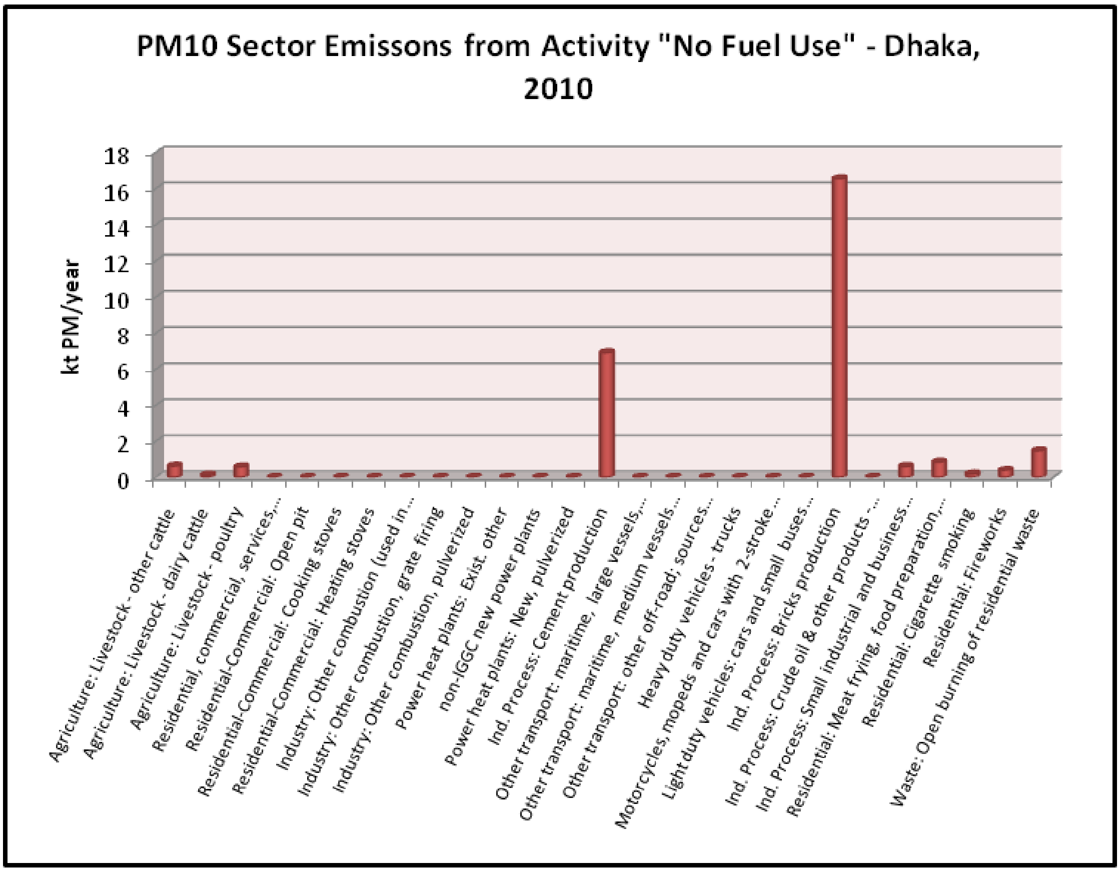


Figure 19: PM_{10} Sector Emission from Activity "No Fuel Use" in Dhaka for 2010.

Figure 16 shows that the activity "fuelwood direct" also has a large contribution of PM_{10} emissions in 2010, approximately 10000 tons PM_{10}. The specific sectors which make up this activity contribution can be seen in Figure 20, where residential cooking stoves is the major source for this activity type at approximately 9000 tons.

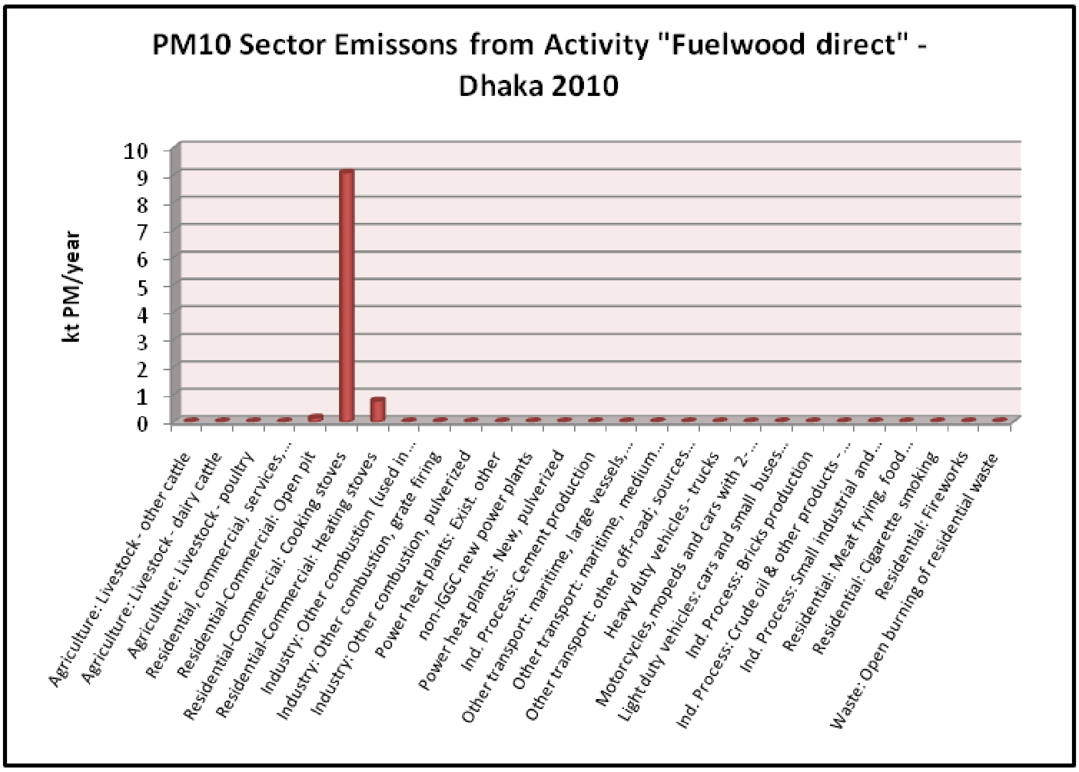


Figure 20: PM_{10} Sector Emissions from Activity "Fuelwood direct" for Dhaka in 2010.

3.2.4 Controls

21 specific mitigation/controls for PM_{10} were available in the model (the same controls as indicated for $PM_{2.5}$) and the results of these control options in regards to no-control options are shown in Figure 21; an explanation of the abbreviations of the controls can be found in Appendix B.

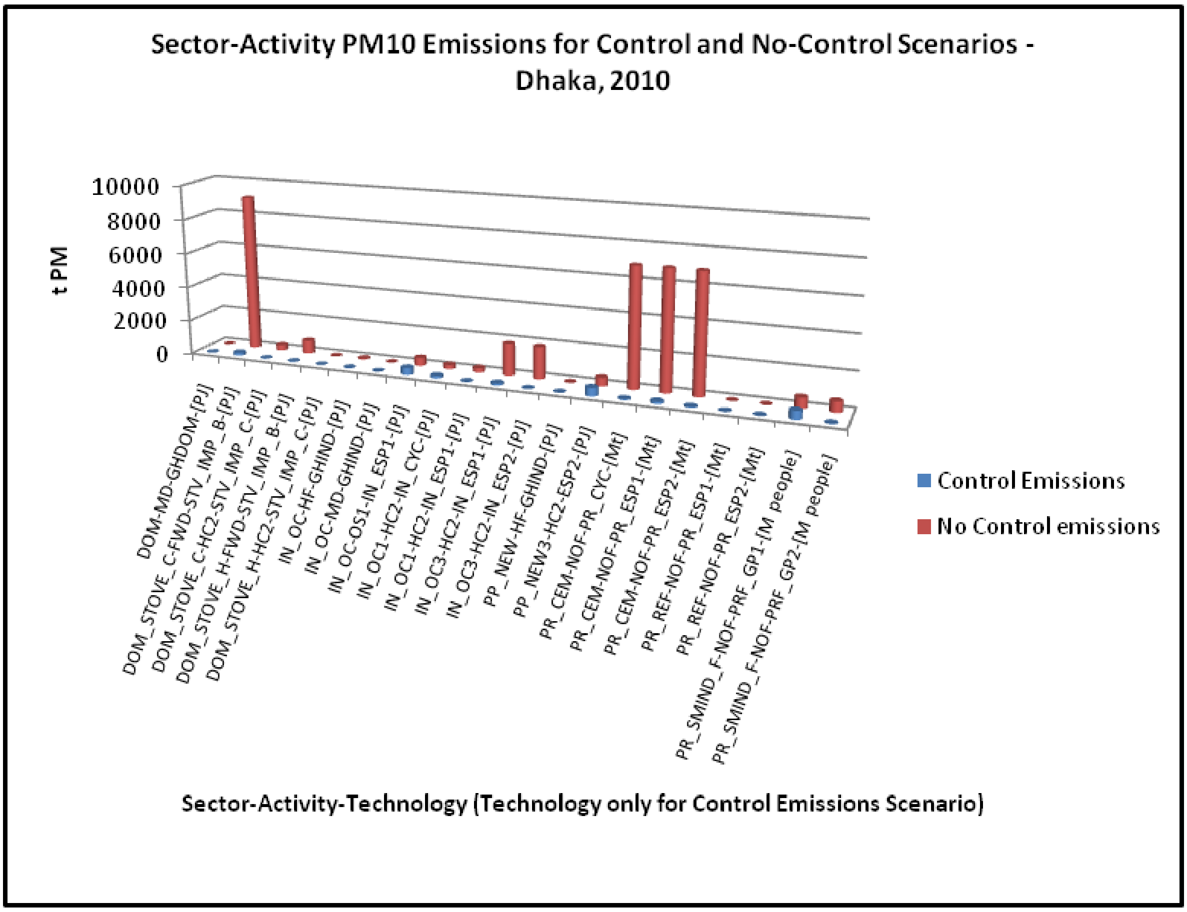


Figure 21: Sector-Activity PM_{10} Emissions for Control and No-control Scenarios in Dhaka for 2010.

A list of the top 10 controls and their PM_{10} removal efficiency can be seen in Table 3. The chosen controls option are applicable to the Industry (industrial process and industry) and Residential sectors; no controls were available for the Transport or Agricultural sector for this particular analysis. Implementation of the top three controls listed in Table 3 (control #1, 6, and 7 - one control for each sector)[7] can reduce PM_{10} emissions for year 2010 by approximately 17600 tons/year. This is more than 1/3 of the total PM_{10} emissions for that year.

Table 3: Top 10 PM_{10} Control options and their emissions removal efficiency in Dhaka for the year 2010.

Control Measure		Total PM_{10} emissions		
Name	**Abbr**	**with Control (tons/year)**	**without Control (tons/year)**	**Difference (tons/year)**
1. Residential-Commercial: Cooking stoves-Fuelwood direct-Biomass stove improved-[10^15 Joules]	DOM_STOVE_C-FWD-STV_IMP_B-[PJ]	173.38	9076.50	8903.12
2. Residential-Commercial: Cooking stoves-Hard coal, grade 2-Coal stove improved -[10^15 Joules]	DOM_STOVE_C-HC2-STV_IMP_C-[PJ]	11.11	312.76	301.65
3. Residential-Commercial: Heating stoves-Fuelwood direct-Biomass stove improved-[10^15 Joules]	DOM_STOVE_H-FWD-STV_IMP_B-[PJ]	14.60	764.34	749.74
4. Industry: Other combustion, grate firing-Hard coal, grade 2-Electrostatic precipitator: 1 field - industrial combustion-[10^15 Joules]	IN_OC1-HC2-IN_ESP1-[PJ]	2.68	241.10	238.43
5. Industry: Other combustion, pulverized-Hard coal, grade 2-Electrostatic precipitator: 1 field - industrial combustion-[10^15 Joules]	IN_OC3-HC2-IN_ESP1-[PJ]	119.21	1854.05	1734.84
6. Industry: Other combustion, pulverized-Hard coal, grade 2-Electrostatic precipitator: 2 fields - industrial combustion-[10^15 Joules]	IN_OC3-HC2-IN_ESP2-[PJ]	7.70	1854.05	1846.35
7. Ind. Process: Cement production-No fuel use-Cyclone - - industrial process-[Mt]	PR_CEM-NOF-PR_CYC-[Mt]	53.30	6908.91	6855.61
8. Ind. Process: Cement production-No fuel use-Electrostatic precipitator: 1 field - industrial processes-[Mt]	PR_CEM-NOF-PR_ESP1-[Mt]	132.44	6908.91	6776.47
9. Ind. Process: Cement production-No fuel use-Electrostatic precipitator: 2 fields - industrial processes-[Mt]	PR_CEM-NOF-PR_ESP2-[Mt]	51.69	6908.91	6857.23
10. Ind. Process: Small industrial and business facilities - fugitive-No fuel use-Good practice: ind.process - stage 2 (fugitive)-[M people]	PR_SMIND_F-NOF-PRF_GP2-[M people]	20.52	615.49	594.97

[7] Some of the controls cannot be combined because they are not complimentary.

3.2.5 Costs

Costs were determined for each of the 21 controls options and are presented in Figure 13. Table 4 presents the costs of the top PM10 control options listed in Table 3. Costs range from less than 1 Euro up to over 5400 Euros/ton of reduced PM_{10} emission, where the most cost efficient measure is Control #7. The implementation of top control measures #1, 6, and 7 would cost a total of 650000 Euros/year to save 17600 tons PM_{10} emissions/year (1/3 of the total annual PM_{10} emissions for 2010).

Table 4: Top 10 PM_{10} emission control options and their related costs for Dhaka in the year 2010.

Control Measure	Abbr	Cost Meuro/year	tons PM_{10} emission reduced	cost Euro/ton PM_{10} emission reduced
1. Residential-Commercial: Cooking stoves-Fuelwood direct-Biomass stove improved-[10^15 Joules]	DOM_STOVE_C-FWD-STV_IMP_B-[PJ]	0.6170	8903.12	69.30
2. Residential-Commercial: Cooking stoves-Hard coal, grade 2-Coal stove improved -[10^15 Joules]	DOM_STOVE_C-HC2-STV_IMP_C-[PJ]	0.0178	301.65	59.01
3. Residential-Commercial: Heating stoves-Fuelwood direct-Biomass stove improved-[10^15 Joules]	DOM_STOVE_H-FWD-STV_IMP_B-[PJ]	0.0649	749.74	86.56
4. Industry: Other combustion, grate firing-Hard coal, grade 2-Electrostatic precipitator: 1 field - industrial combustion-[10^15 Joules]	IN_OC1-HC2-IN_ESP1-[PJ]	0.0089	238.43	37.33
5. Industry: Other combustion, pulverized-Hard coal, grade 2-Electrostatic precipitator: 1 field - industrial combustion-[10^15 Joules]	IN_OC3-HC2-IN_ESP1-[PJ]	0.1366	1734.84	78.74
6. Industry: Other combustion, pulverized-Hard coal, grade 2-Electrostatic precipitator: 2 fields - industrial combustion-[10^15 Joules]	IN_OC3-HC2-IN_ESP2-[PJ]	0.0309	1846.35	16.74
7. Ind. Process: Cement production-No fuel use-Cyclone - -industrial process-[Mt]	PR_CEM-NOF-PR_CYC-[Mt]	0.0008	6855.61	0.12
8. Ind. Process: Cement production-No fuel use-Electrostatic precipitator: 1 field - industrial processes-[Mt]	PR_CEM-NOF-PR_ESP1-[Mt]	0.0192	6776.47	2.83
9. Ind. Process: Cement production-No fuel use-Electrostatic precipitator: 2 fields - industrial processes-[Mt]	PR_CEM-NOF-PR_ESP2-[Mt]	0.0234	6857.23	3.41
10. Ind. Process: Small industrial and business facilities -fugitive-No fuel use-Good practice: ind.process - stage 2 (fugitive)-[M people]	PR_SMIND_F-NOF-PRF_GP2-[M people]	3.2304	594.97	5429.48

3.3 SO_2

SO_2 emissions for Dhaka are modeled to reach 113000 tons/year in 2030, where the current modeled level for 2010 is 34000 tons (Figure 22). These SO_2 emission will be analyzed for the particular activity levels, sector levels, and sector emissions from specific activities making up these total emission values.

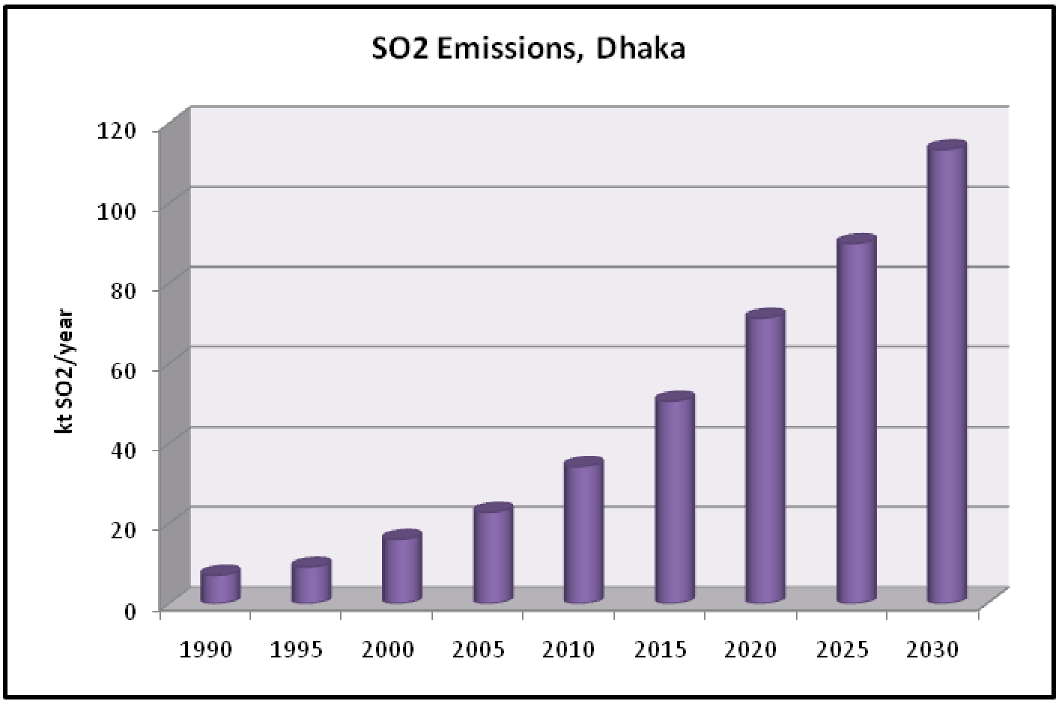


Figure 22: SO_2 Emission for Dhaka, 1990-2030.

3.3.1 Activity

The SO_2 emissions (as shown in Figure 22) can be broken down into specific activities (source fuel types) as presented in Figure 23. The “hard coal” activity represents the greatest contribution of SO_2 emissions which is greatly increasing over time, reaching 74000 tons/year SO_2 in 2030. The second largest contributions of SO_2 emissions comes from the “heavy fuel oil”, “natural gas”, and “medium distillates” activities, which are gradually increasing over time, estimated to be closer to 12000, 14000, and 8000 tons in 2030 respectively. The other activities associated with SO_2 emissions have minimal emission contributions in comparison to the previous activities mentioned.

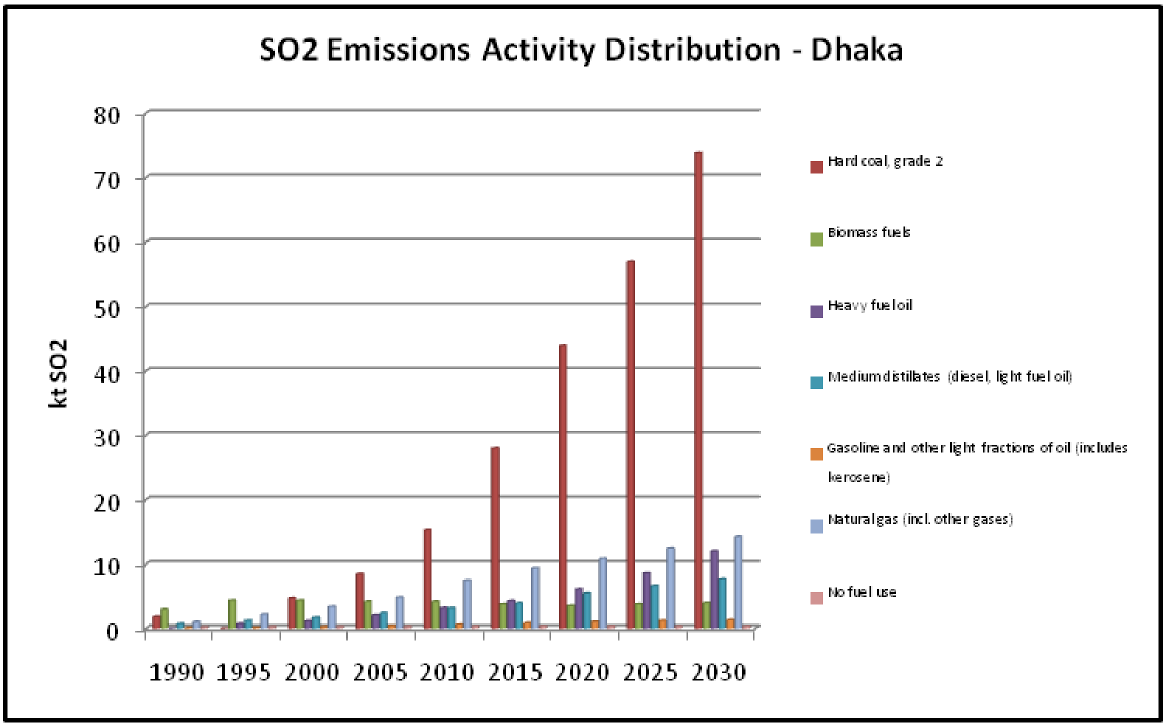


Figure 23: SO_2 Emissions Activity Distribution for Dhaka from 1990-2030.

The modeled situation for the associated activities for SO_2 emissions for 2010 (Figure 24) show that the "Hard coal" activity (15000 tons) represents approximately twice as much of the SO_2 emissions as the next greatest activity "natural gas" (7000 tons) for that year, with other activities of "Biomass fuels", "Heavy fuel oil", and "Medium distillates" very similar at approximately 3000 tons each.

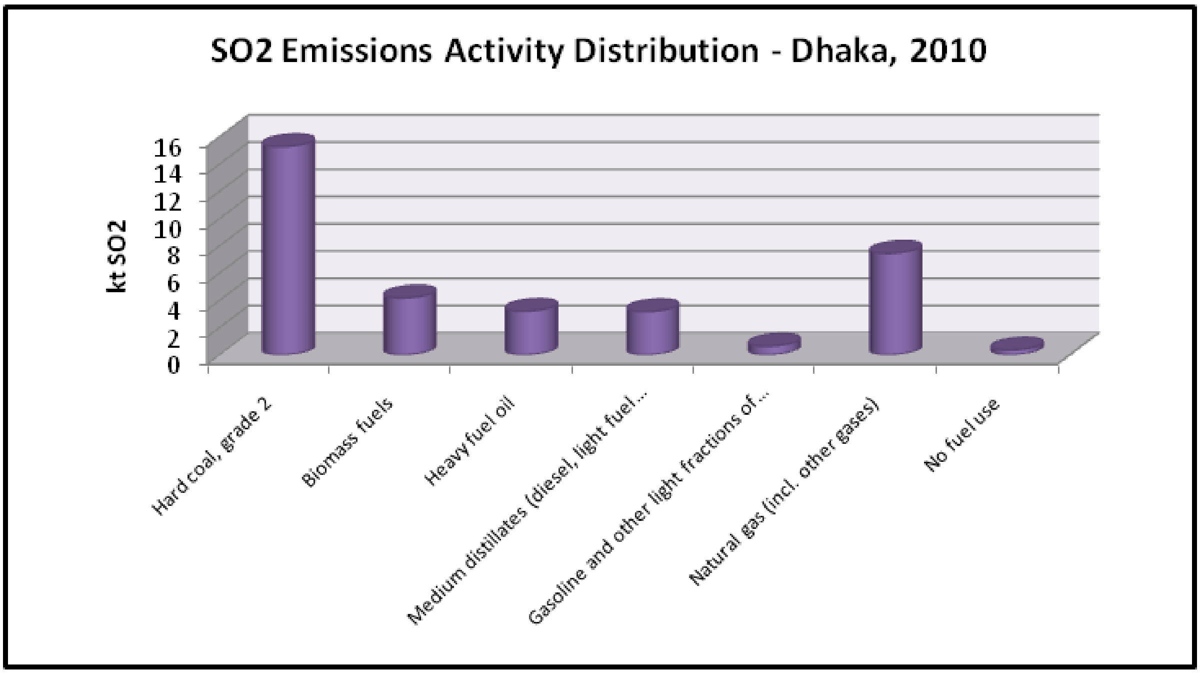


Figure 24 SO_2 Emissions Activity Distribution for Dhaka for 2010.

3.3.2 Sector

The SO_2 emissions can be broken down in to *general* sectors as presented in Figure 25, which shows a large increase over time from the industrial sector, while the transport and residential sectors have a much smaller increase in comparison. Here the transport sector displays a low contribution of SO_2 emissions, holding under 4000 tons/year. A graph displaying the *specific* sector distributions of SO_2 emissions from 1990-2030 is in Appendix D.

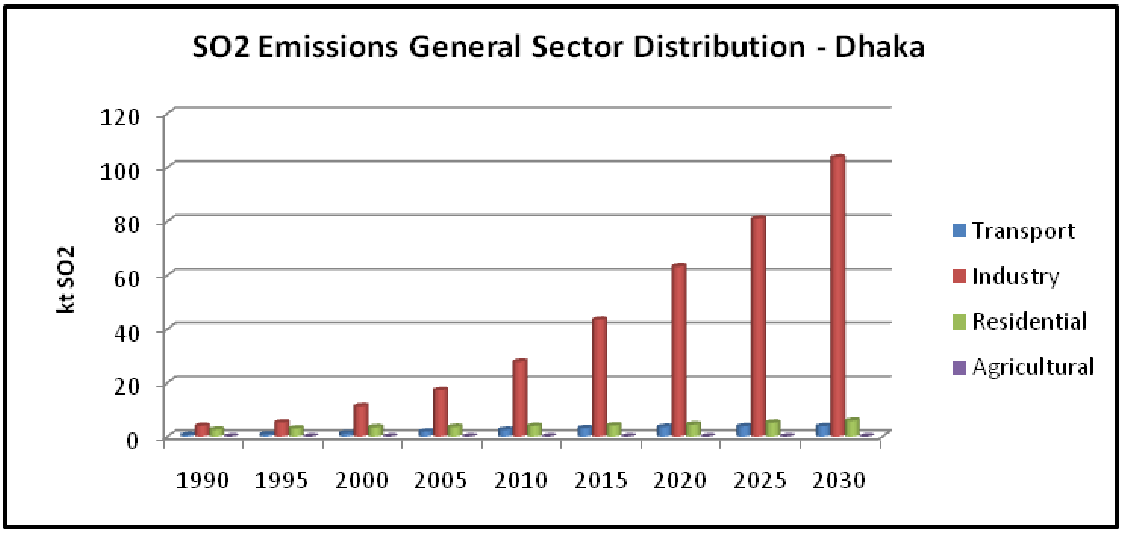


Figure 25: SO_2 Emissions General Sector Distribution for Dhaka from 1990-2030.

The *specific* sector distribution for 2010 (Figure 26) shows that a majority of SO_2 emissions comes from combustion within Industry, approximately 15000 tons/year. Power plants also make up a large share of the SO_2 emission at approximately 12000 tons/year.

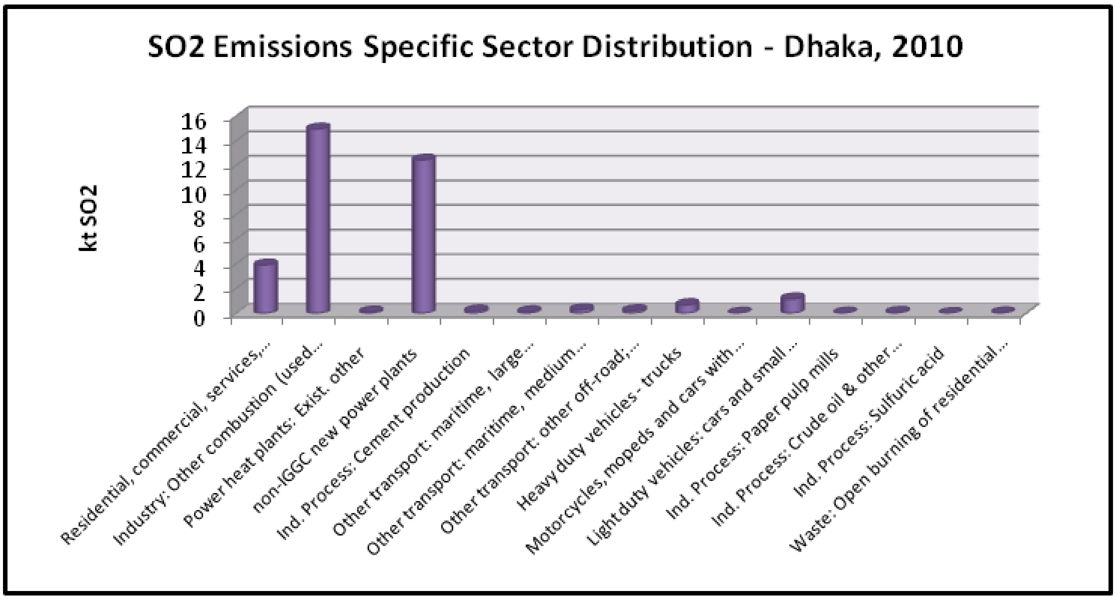


Figure 26: SO_2 Emissions Specific Sector Distribution for Dhaka for 2010.

3.3.3 Sector-Activity

Figure 24 shows that the activity “hard coal” has the greatest contribution to SO_2 emissions in 2010, over 14000 tons SO_2. The specific sectors which make up this activity contribution can be seen in Figure 27, where power plants are the major source for this activity type (12000 tons/year), followed by industry combustion (approximately 3000 tons/year).

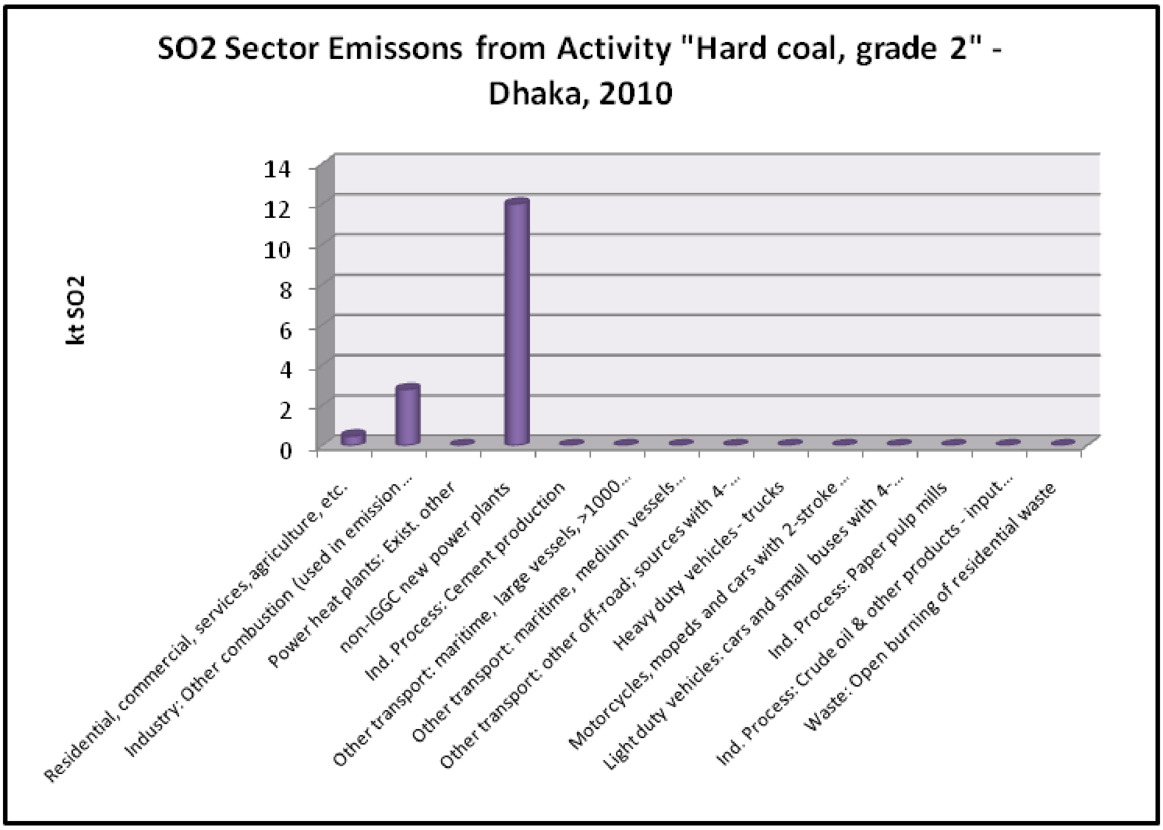


Figure 27: SO_2 Sector Emission from Activity “Hard coal, grade 3” in Dhaka for 2010.

Figure 24 also shows that the activity “natural gas” has a large contribution of SO_2 emissions in 2010, approximately 7000 tons SO_2. The specific sectors which make up this activity contribution can be seen in Figure 28, where the industry combustion sector makes up the total 7000 tons from this specific activity.

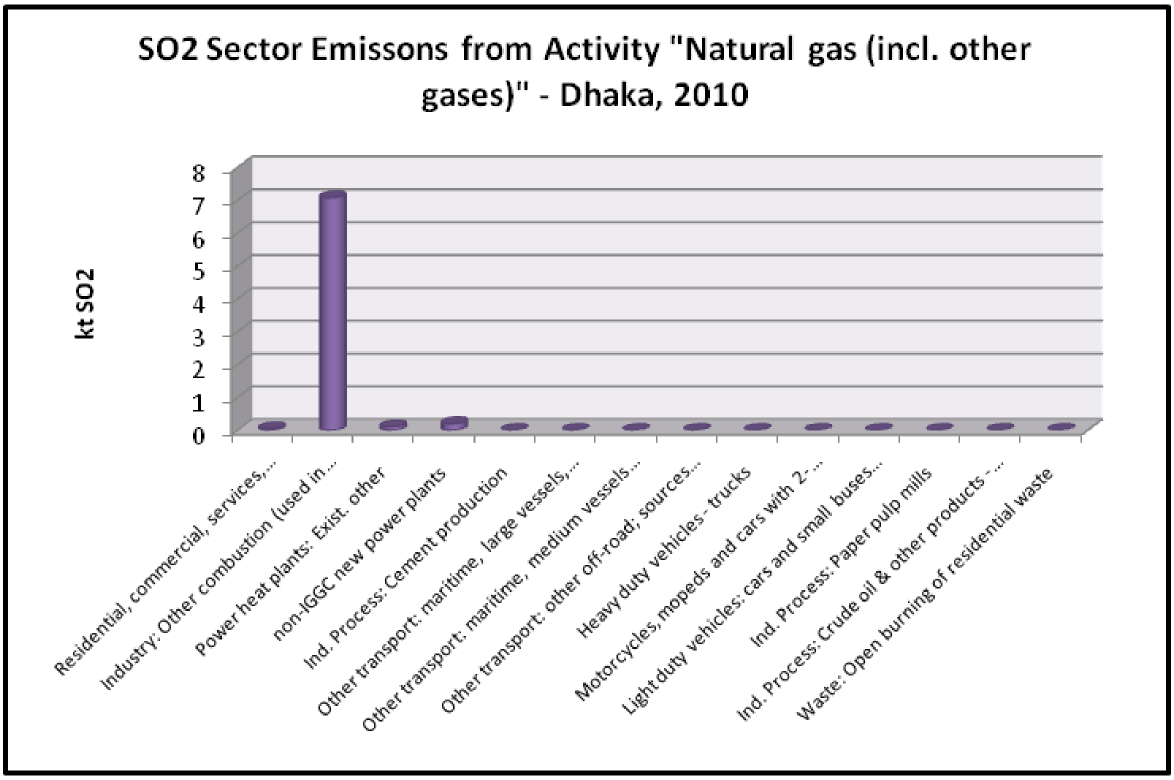


Figure 28: SO_2 Sector Emissions from Activity "Natural Gas" for Dhaka in 2010.

3.3.4 Controls and Costs

Removal efficiency for controls listed in the model were 0%, which means that no control data is available, thus no cost data is also available.

3.4 NO_X

NO_X emissions for Dhaka are modeled to reach 60000 tons/year in 2030, where the current modeled level for 2010 is 30000 tons/year (Figure 29). These NO_X emission will be analyzed for the particular activity levels, sector levels, and sector emissions from specific activities making up these total emission values.

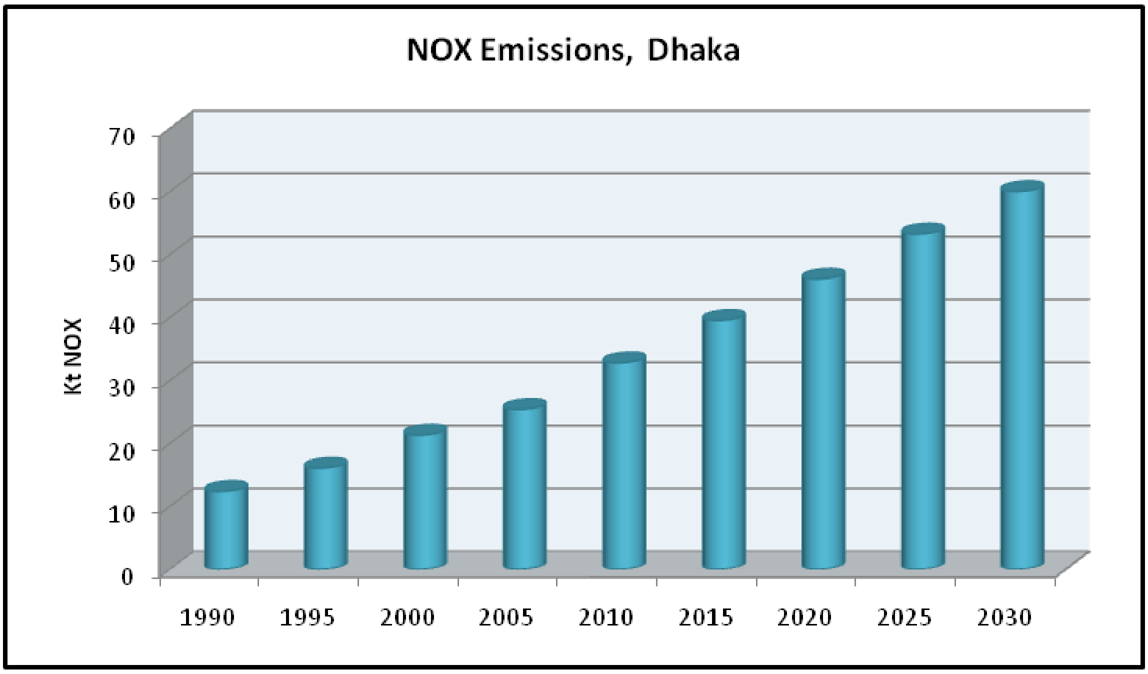


Figure 29: NO_X Emission for Dhaka, 1990-2030.

3.4.1 Activity

The NO_X emissions (as shown in Figure 29) can be broken down into specific activities (source fuel types) as presented in Figure 30. The "natural gas" activity represents the greatest contribution of NO_X emissions which is greatly increasing over time, reaching almost 16000 tons/year NO_X in 2030. The second largest contributions of NO_X emissions comes from the "Gasoline", "hard coals", and "medium distillates" activities, which are gradually increasing over time, estimated to be closer to 12000, 16000, and 8000 tons/year in 2030 respectively. The "biomass fuels" activity was a significant contribution to NO_X emissions prior to 2010, but since is predicted to decline as a source of NO_X emissions. The other activities associated with NO_X emissions ("heavy fuel oil" and "no fuel use") are have minimal emission contributions in comparison to the previous activities mentioned.

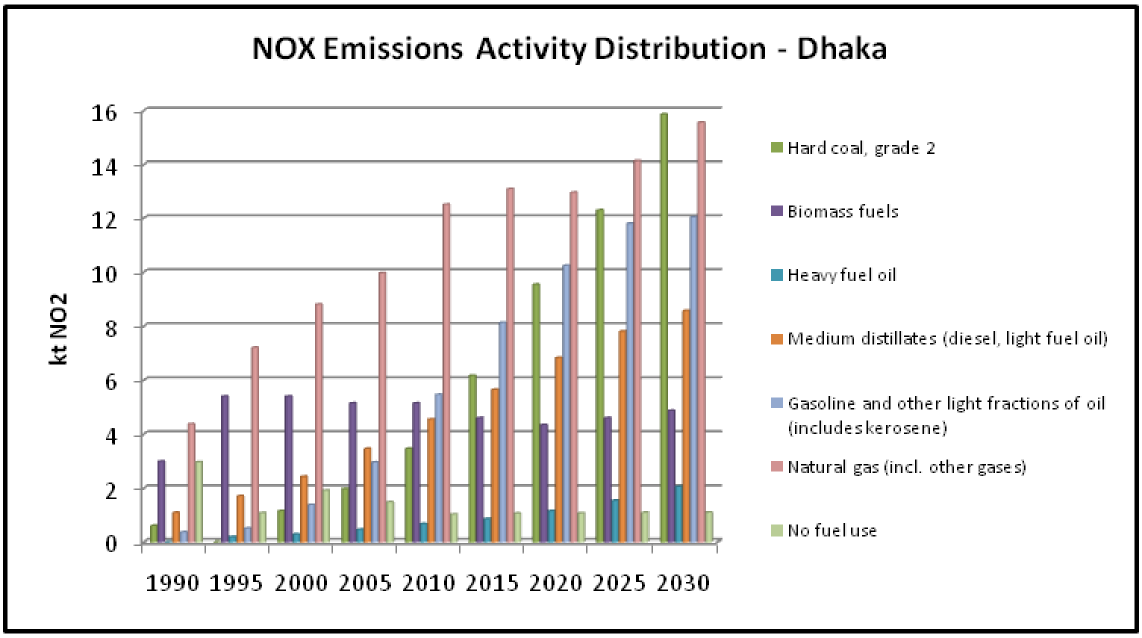


Figure 30: NO_X Emissions Activity Distribution for Dhaka from 1990-2030.

The modeled situation for the associated activities for NO_X emissions for 2010 (Figure 31) show that the “Natural gas” activity (12500 tons/year) represents more than twice as much of the NO_X emissions as the next greatest activity “Gasoline” (5500 tons/year) for that year, with other activities of “Biomass fuels”, “Hard coal”, and “Medium distillates” very similar at approximately 4-5000 tons/year each.

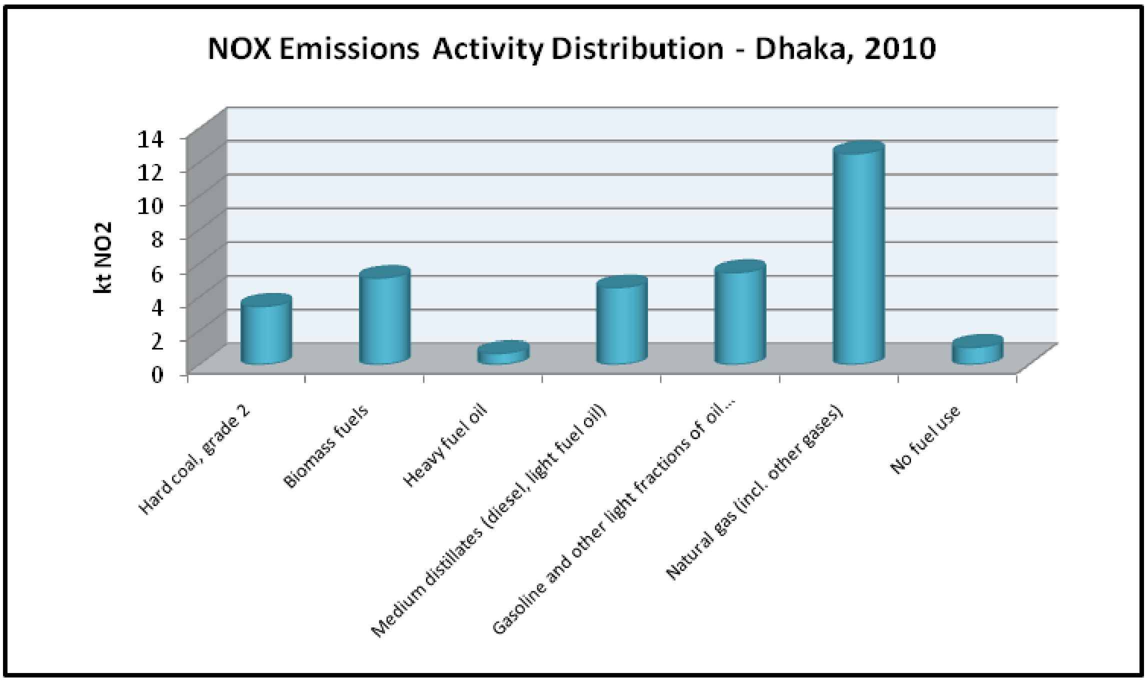


Figure 31: NO_X Emissions Activity Distribution for Dhaka for 2010.

3.4.2 Sector

The NO_X emissions can be broken down in to *general* sectors as presented in Figure 32, which shows a large increase over time from the industrial sector, while the transport sector is also increasing as well. The industrial sector is estimated to contribute with over 35000 tons/year NO_X in the year 2030. A graph displaying the *specific* sector distributions of SO_2 emissions from 1990-2030 is in Appendix E.

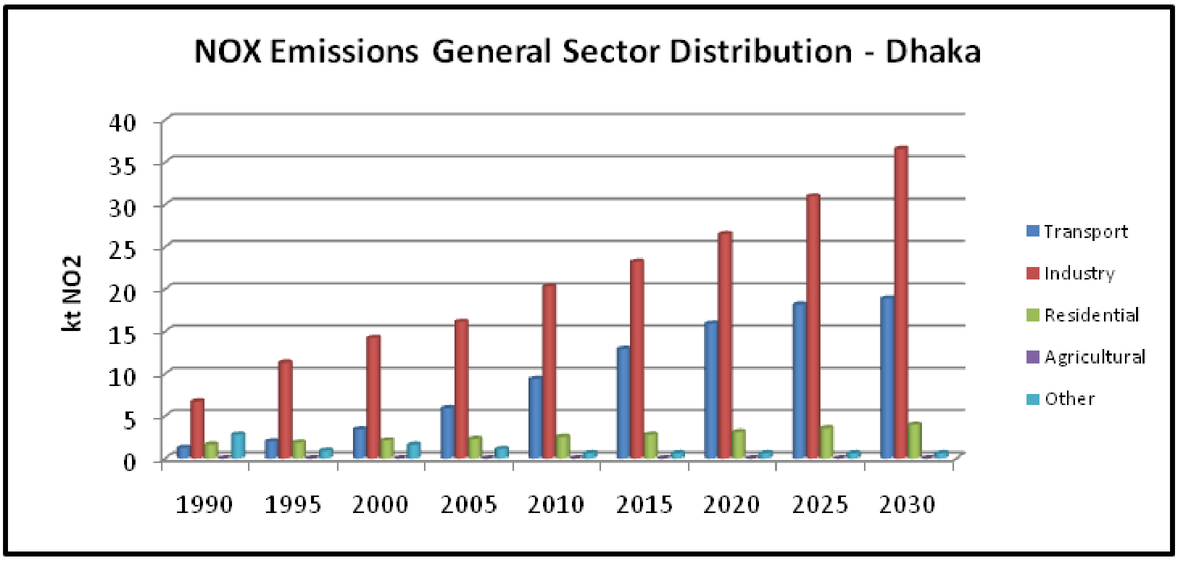


Figure 32: NO_X Emissions General Sector Distribution for Dhaka from 1990-2030.

The *specific* sector distribution for 2010 (Figure 33) shows that a majority of NO_X emissions comes from combustion within industry, approximately 12000 tons/year. Power plants and light/heavy duty vehicles also make up a large share of the NO_X emission at approximately 7000 tons/year each for 2010.

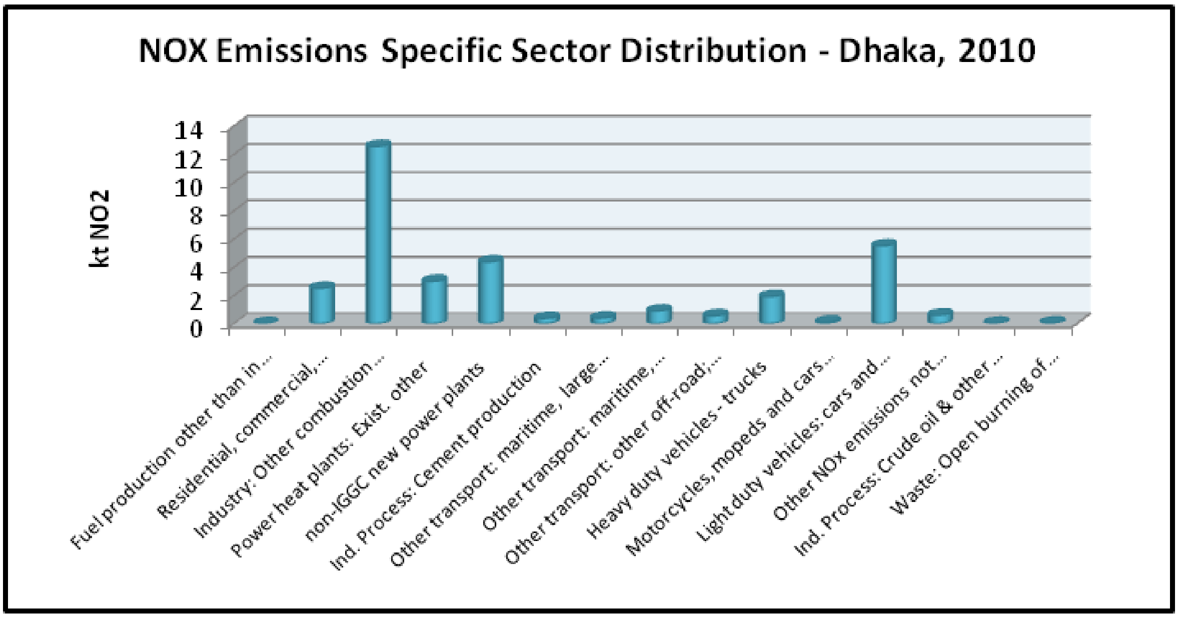


Figure 33: NO_X Emissions Specific Sector Distribution for Dhaka for 2010.

3.4.3 Sector-Activity

Figure 31 shows that the activity “natural gas” has the greatest contribution of NO_X emissions in 2010, at approximately 12000 tons/year NO_X. The specific sectors which make up this activity contribution can be seen in Figure 34, where industrial combustion is the major source for this activity type (7000 tons/year), followed by power heat plants (3000 tons/year), and new power plants (1500 tons/year).

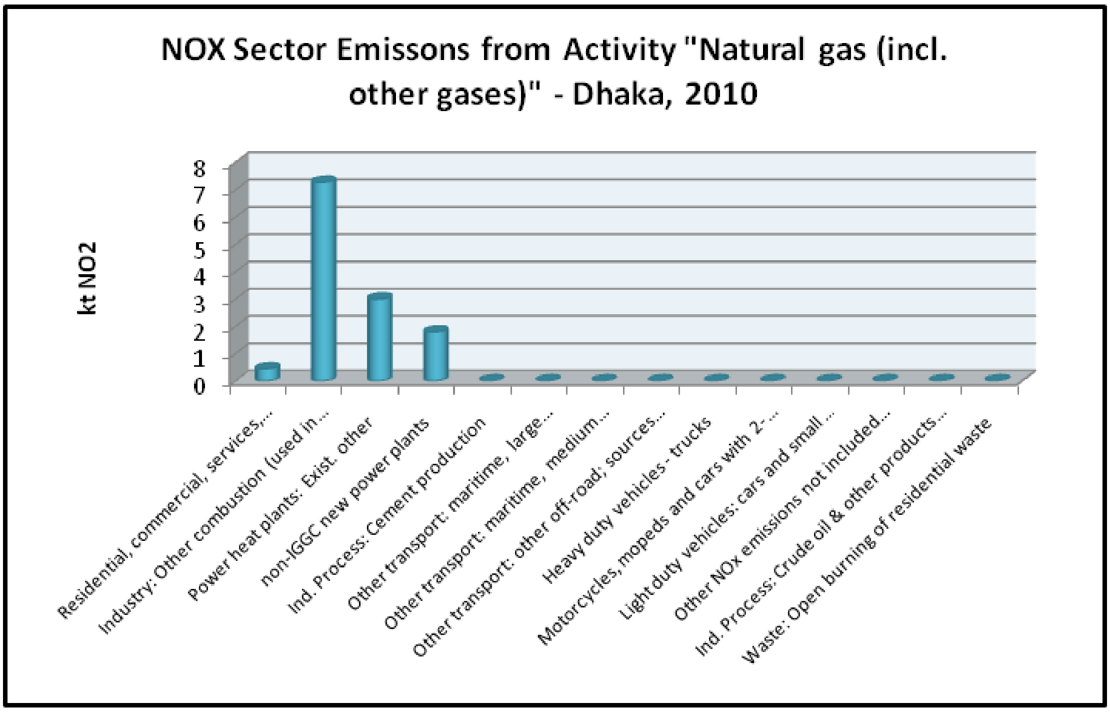


Figure 34: NO_X Sector Emission from Activity “Natural gas” in Dhaka for 2010.

Figure 31 shows that the activity “Gasoline and other light fractions of oil” also has a fair contribution of NO_X emissions in 2010, approximately 5500 tons/year NO_X. The specific sectors which make up this activity contribution can be seen in Figure 35, where the light duty vehicle sector makes up a majority of the total 7000 tons/year from this specific activity.

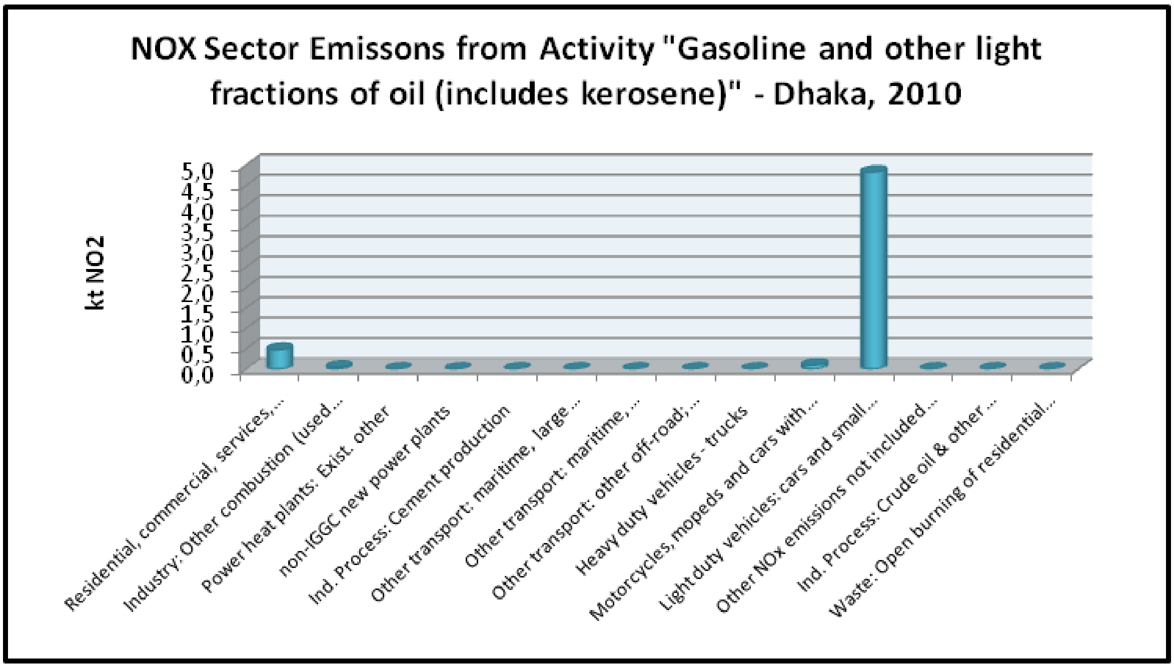


Figure 35: NO_X Sector Emissions from Activity "Natural Gas" for Dhaka in 2010.

Figure 31 also shows that the activity "Medium distillates" has a fair contribution of NO_X emissions in 2010, approximately 4500 tons/year NO_X. The specific sectors which make up this activity contribution can be seen in Figure 36, where the heavy duty vehicle sector makes up a almost 2000 tons/year, followed by maritime transport medium-vessels (1000 tons/year).

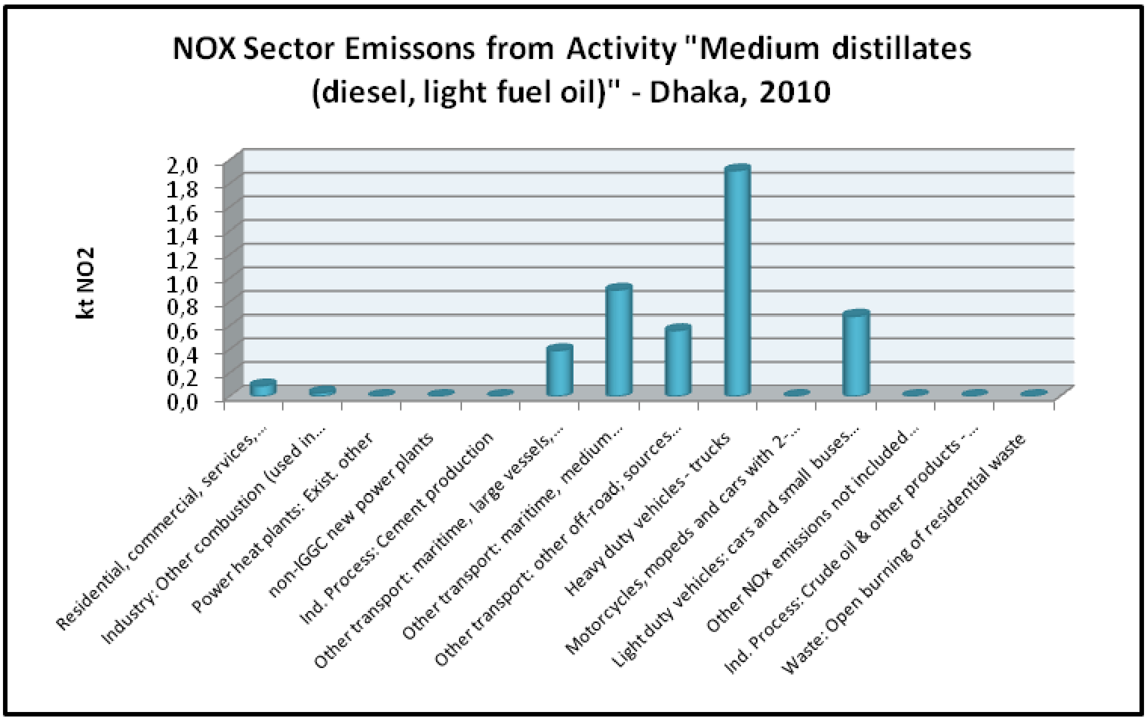


Figure 36: NO_X Sector Emissions from Activity "Natural Gas" for Dhaka in 2010.

3.4.4 Controls and Costs

Removal efficiency for controls listed in the model where 0%, which means that no control data is available, thus no cost data is also available.

3.5 GHG's

GHG emissions for Dhaka are modeled to reach 42 million tons/year (CO_2 equivalent) in 2030, where the current modeled level for 2010 is 23 million tons/year (CO_2 equivalent) (Figure 37). Approximately 2/3 of the GHGs is CO_2 in 2010, and in 2020 it is 3/4 CO_2 (Figure 4). These GHG emissions will be analyzed for the particular activity levels, sector levels, and sector emissions from specific activities making up these total emission values.

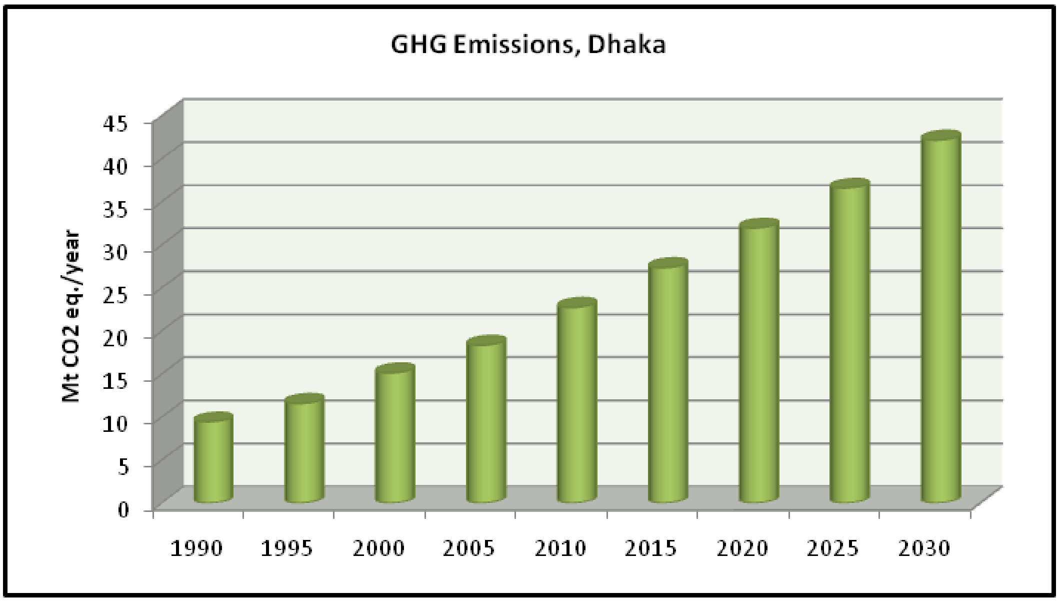


Figure 37: GHG Emissions for Dhaka, 1990-2030.

3.5.1 Activity

The GHG emissions (as shown in Figure 37) can be broken down into specific activities (source fuel types) as presented in Appendix F. The “natural gas” activity represents the greatest contribution of GHG emissions which is greatly increasing over time, reaching almost 19 million tons/year (CO_2 equivalent) in 2030. The second largest contributions of GHG emissions comes from the “hard coal” activity which is gradually increasing over time, estimated to be closer to 10 million tons/year (CO_2 equivalent) in 2030. The other activities associated with GHG emissions (“heavy fuel oil”, “cattle”, and “area of activity – agriculture”) have minimal emission contributions in comparison to the previous activities mentioned.

The modeled situation for the associated activities for GHG emissions for 2010 (Figure 38) shows that the “Natural gas” activity (11 million tons/year CO_2 equivalent) represents by far the greatest GHG emissions in comparison to the next greatest activities of “Area of activity - agriculture” (2.6 million tons/year CO_2 equivalent), “Hard coal” (2.6 million tons/year CO_2 equivalent), and “other cattle – not included cows” (1.6 million tons/year CO_2 equivalent).

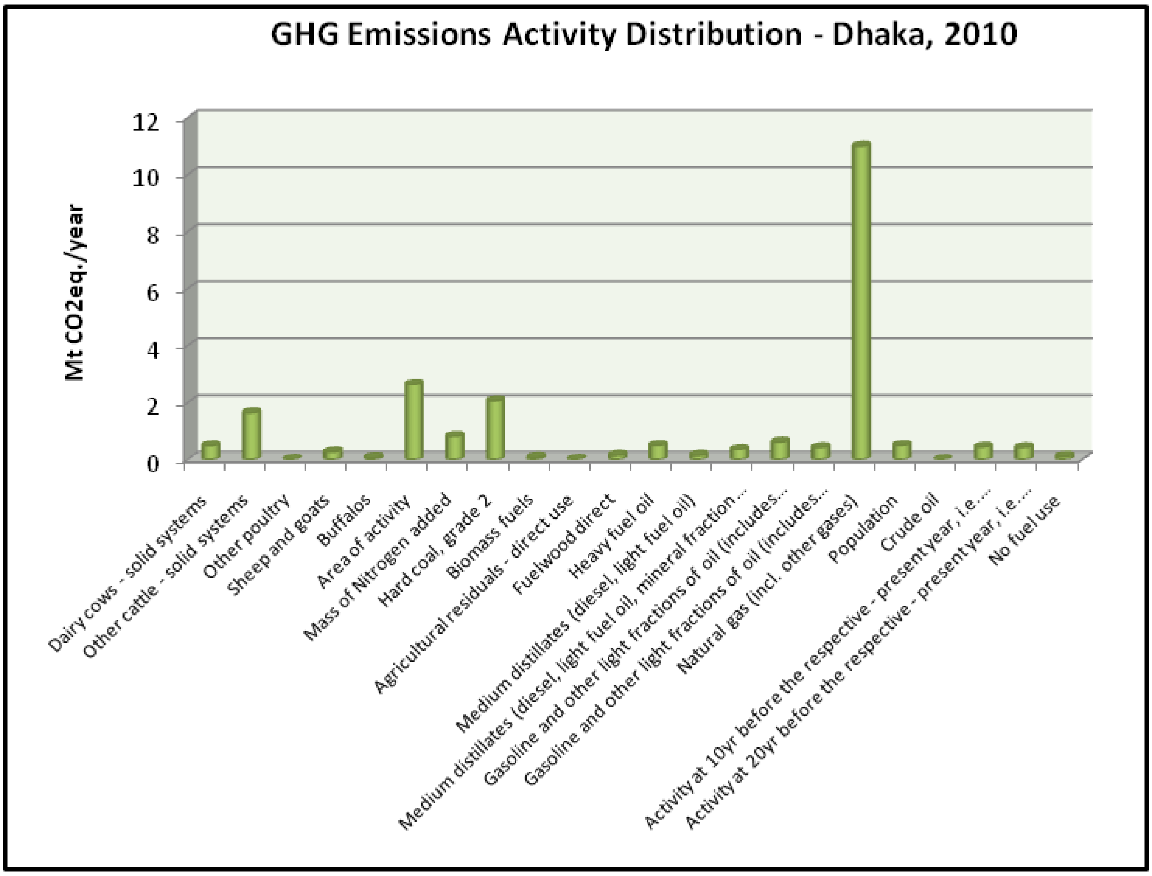


Figure 38: GHG Emissions Activity Distribution for Dhaka for 2010.

3.5.2 Sector

The GHG emissions can be broken down in to *general* sectors as presented in Figure 39, which shows a large increase over time from the industrial sector, while the transport, residential, and agricultural sectors are just slightly increasing over time. The agricultural sector is estimated to have the greatest contribution of GHGs in 1990, but by 2005 the industrial sector had almost twice as much emissions as the agricultural sector. The industrial sector is estimated to contribute over 30 million tons/year GHG (CO_2 equivalent) in the year 2030, which is 5 times as much emissions as the next highest sector for that year (agriculture). A graph displaying the *specific* sector distributions of GHG emissions from 1990-2030 is in Appendix G.

The *specific* sector distribution for 2010 (Figure 40) shows that a majority of GHG emissions comes from the “other combustion” and “non-IGGC[8] plants“ within industry, over 10 million tons/year (CO_2 equivalent). Smaller individual agricultural activities are the next greatest specific sectors contributing to GHG emissions, together equaling over 5 million tons/year (CO_2 equivalent).

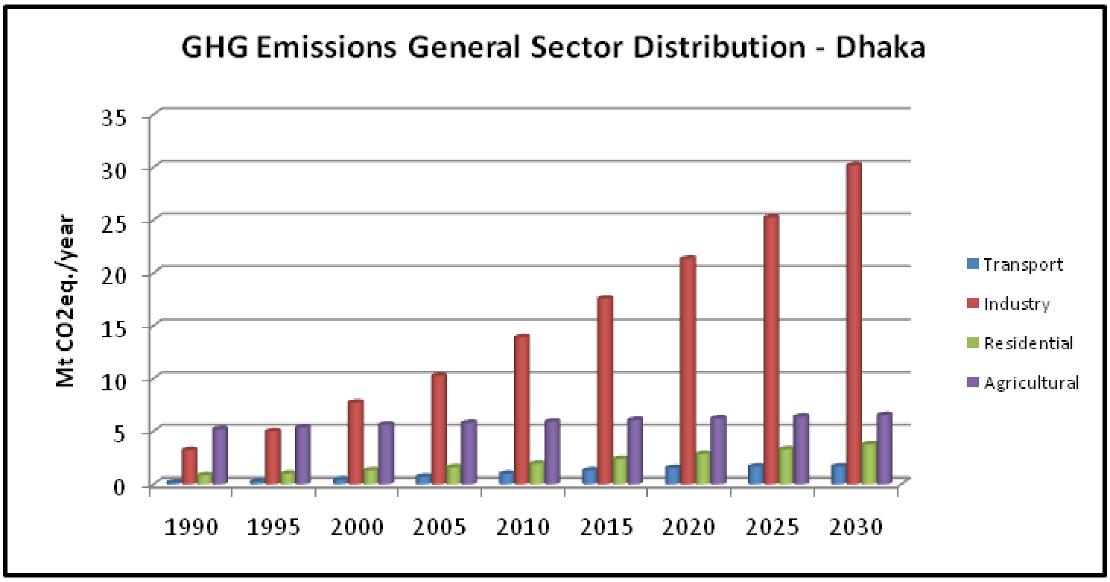


Figure 39: GHG Emissions General Sector Distribution for Dhaka from 1990-2030.

[8] IGGC probably refers to IGCC (Integrated Gasification Combined Cycle).

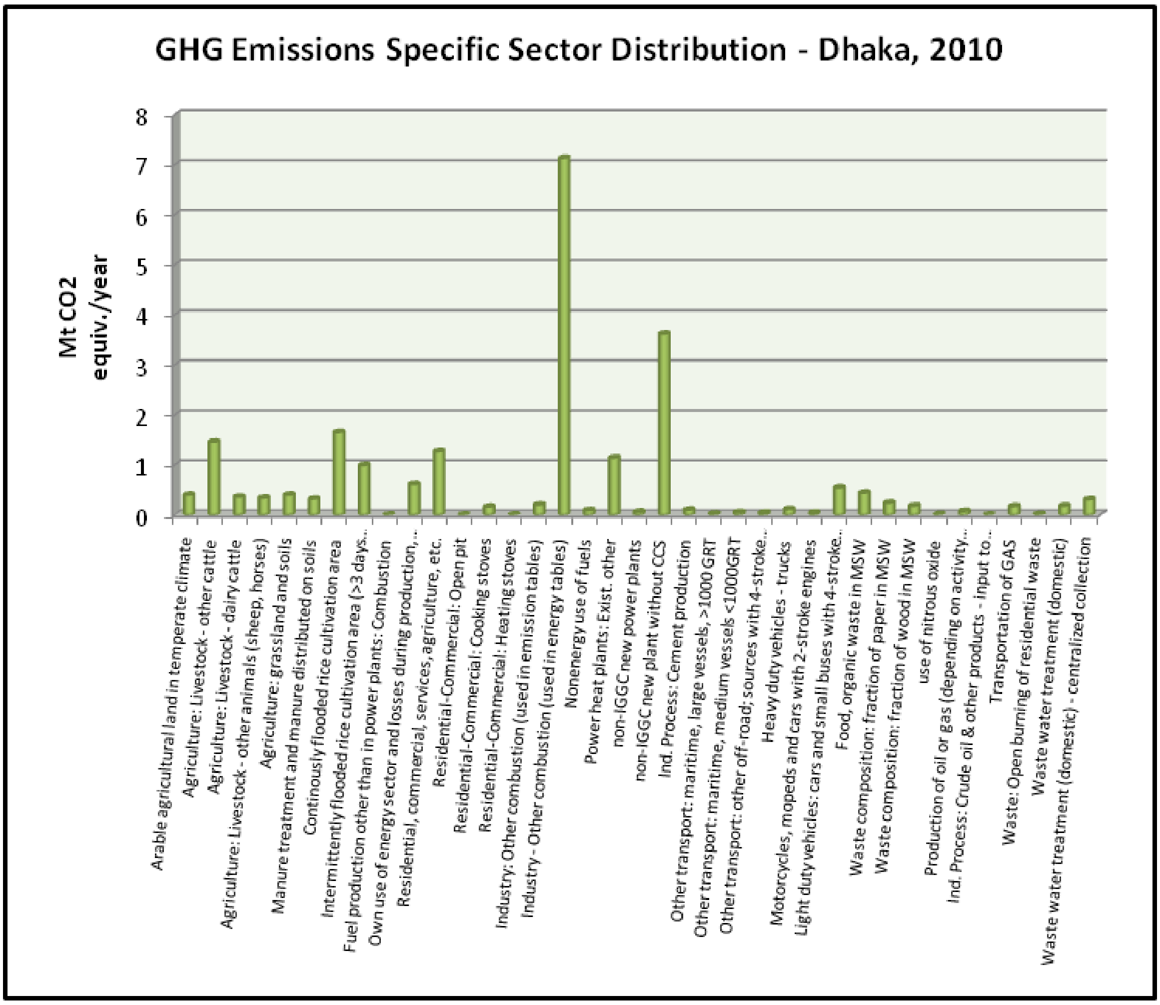


Figure 40: NO_X Emissions Specific Sector Distribution for Dhaka for 2010.

3.5.3 Sector-Activity

Figure 38 shows that the activity "natural gas" has the greatest contribution of GHG emissions in 2010, at approximately 11 million tons/year. The specific sector which makes up this activity contribution is industrial combustion, and the increase of these emissions over time can be seen in Figure 41. Hard coals is the activity with the second greatest contribution to GHG, where the specific sector of new power plants makes up most of the emissions for this activity; the increase of this specific sector over time is seen in Figure 42.

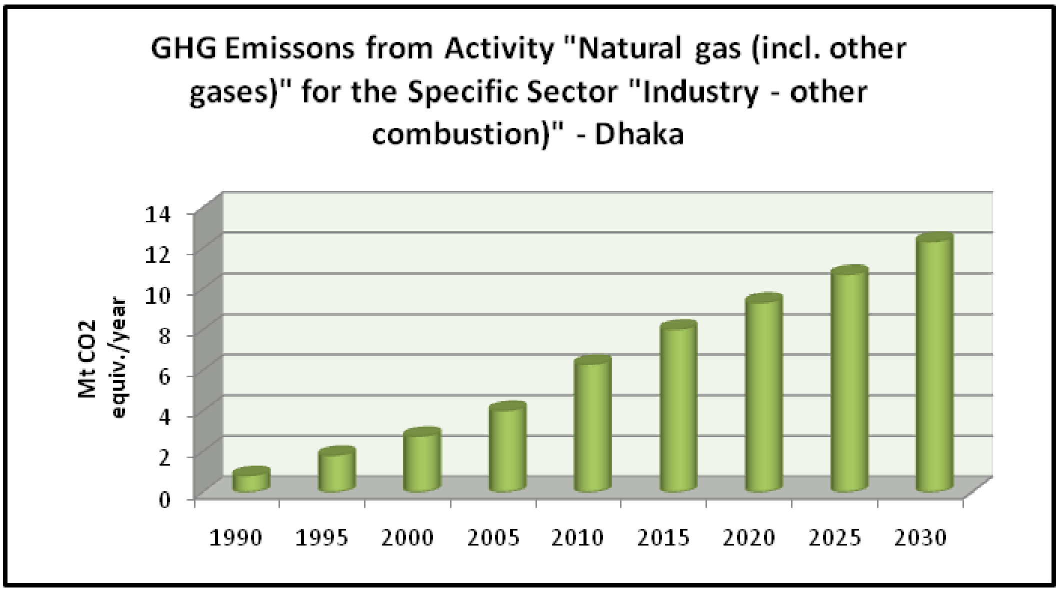


Figure 41: GHG Emission from Activity "Natural gas" for the Specific Sector "Industry – other combustion" in Dhaka from 1990-2030.

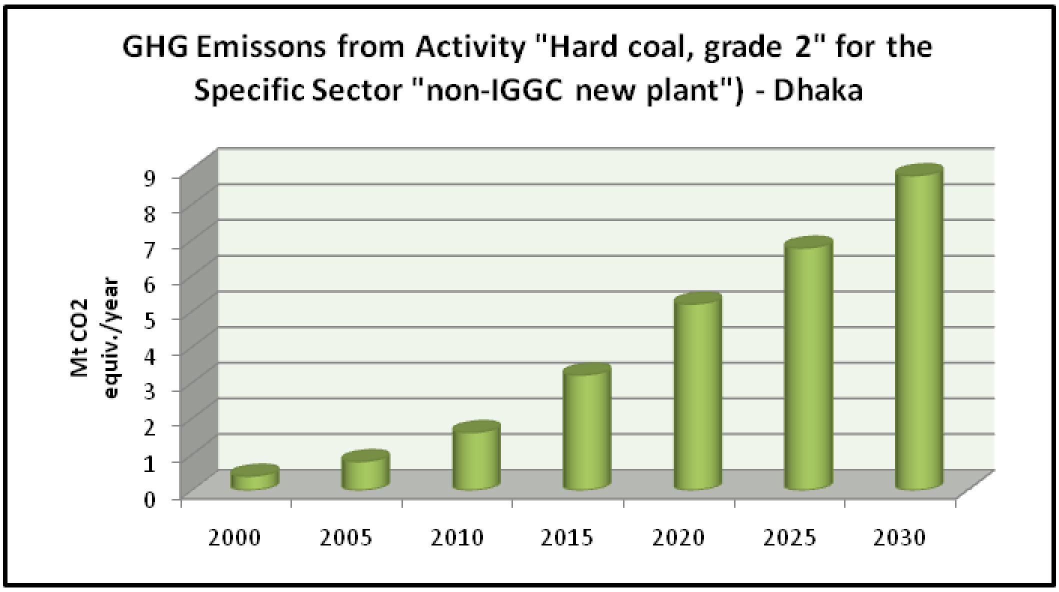


Figure 42: GHG Emission from Activity "Natural gas" for the Specific Sector "non-IGGC new plant" in Dhaka from 2000-2030.

3.5.4 Controls and Costs

No control strategies are available for GHGs in the model.

4 Conclusion and Discussion

The total top-down emissions for PM, SO_2, NO_X, and GHGs for 2010, as well as the decadal trends, have been presented for Dhaka. The top sectors, sub-sectors, and activities making up the emissions for each pollutant have also been analyzed. The overall results for this analysis for 2010 in Dhaka is summarized in Table 5.

Table 5: Results summary table for contribution of sectors/activities to emissions of $PM_{2.5}$, PM_{10}, SO_2, NO_X, and GHGs (Dhaka, 2010).

	Total Emissions (tons/yr)	Top Sectors (General)	Sector emissions (tons/yr)	Top Activities (fuels)	Activity emissions (tons/ yr)	Top Sub-sectors for related Activity	Sub-sector emissions (tons/year)
$PM_{2.5}$	35000	Industry	19000	No Fuel Use	20000	Bricks Production Cement production	15000 3000
		Residential	13000	Fuelwood direct	10000	Residential cooking	9000
PM_{10}	45000	Industry	27000	No Fuel Use	28000	Bricks Production Cement production	17000 7000
		Residential	15000	Fuelwood direct	10000	Residential cooking	9000
SO_2	34000	Industry	28000	Hard coal	15000	New power plants Industrial combustion	12000 2000
				Natural gas	7000	Industrial combustion	7000
NO_X	30000	Industry	20000	Natural gas	12000	Industrial combustion	7000
						Power plants	4500
		Transport	9000	Gasoline	5000	Light duty vehicles	4500
				Medium distil.	4000	Heavy duty vehicles	2000
GHGs	23000000	Industry	14000000	Natural gas	11000000	Industrial combustion	7000000
		Agriculture	6000000	Hard coal	2000000	New power plants	1300000

Initially it was thought that GAINS was producing a major underestimation of PM emissions for the transportation sector, as first stated in Sivertsen (2010). After field visits to Dhaka as well as through additional research, it was discovered that up to 73% of the traffic sources (not counting motor bikes) runs on CNG (Wadud, 2011), which would explain the low PM estimations from GAINS for this sector.[9] On the contrary, as initially expected, the majority of PM emissions are originating from the brick production industry. However, it was surprising that residential cooking stoves also show a large contribution, making up almost 10 times the PM contribution compared to the transport related specific sectors. So it can be generally concluded that PM emissions come from the industry and residential sectors (industry is slowly taking over as the dominant source sector),primarily from brick kiln production, and some cement production (industrial sector) and from residential cooking stoves (residential sector).

[9] It should be noted that it is estimated that up to 6000 premature deaths were avoided in 2009 due to the switch to CNG from fossil fuels (Zia et al., 2011).

As expected, a majority of the SO_2 and NO_X emissions are generated from the Industry sector, originating from combustion of natural gas and hard coal in power plants and industry. In addition some NO_X emissions are generated by the Transport sector, due to combustion of gasoline and other medium distillates in light and heavy duty vehicles.

Also as expected, a majority of the GHG emissions are coming from Industry (including power generation) and Agriculture, following the typical global pattern of approximately 25% of GHGs from the Agricultural sector, and 50% from Industry (including power) (WRI, 2005).

Overall, emissions in Dhaka are greatly increasing for the selected pollutants over time, where these emission rates vary for each sector. Comparing the emissions for 2010 and 2030 broken down into each sector (Table 6), shows that Residential and Transport related emissions of $PM_{2.5}$ and PM_{10} will decrease by 2030, and Industrial emission will greatly increase, while Agricultural based emissions will increase for PM_{10} but decrease for $PM_{2.5}$. SO_2, NO_X, and GHG emissions are increasing for all sectors by 2030, while as expected, SO_2 and GHG emissions are increasing at a greater rate within the Industrial sector, and NO_X emissions are increasing at a greater rate in the Transport sector.

Table 6: Summary of sector emissions (ktons) for each pollutant (from 2010 and 2030 in Dhaka) and percent difference.

	Sector												TOTAL		
	Transport			Industry			Residential			Agriculture					
	2010	2030	diff	2010	2030	diff	2010	2030	diff	2010	2030	diff	2010	2030	diff
$PM_{2.5}$	1.36	1.29	-5%	19.47	36.45	+87%	13.03	9.78	-25%	1.41	1.18	-16%	35.26	48.70	+38%
PM_{10}	1.50	1.47	-2%	27.19	49.71	+83%	14.91	11.16	-25%	1.36	1.68	+24%	44.95	64.02	+42%
SO_2	2.50	3.84	+53%	27.82	103.71	+273%	3.94	5.93	+50%	*n/a*	*n/a*	*n/a*	34.26	113.48	+231%
NO_2	9.38	18.90	+102%	20.31	36.57	+80%	2.54	3.99	+57%	*n/a*	*n/a*	*n/a*	32.82	60.05	+83%
GHG*	0.97	1.66	+71%	13.89	30.18	+117%	1.93	3.79	+96%	5.92	6.54	10%	22.71	42.17	+86%

**MTons CO_2 equivalent*

It can be valuable to research these sector emission results further between 2010 and 2030 using the GAINS model to determine which activities (fuels) and sub-sectors that are contributing to the increases (and decreases) in emissions over time in Dhaka.

As a basis to achieve a more integrated management of air pollution in Dhaka, control measures and their costs were also evaluated. The overall results for the mitigation measures and associated costs for Dhaka in 2010 is summarized in Table 7 for $PM_{2.5}$ and PM_{10}.

Table 7: Total emissions, emission reduction potential for the top mitigation measures and related costs for $PM_{2.5}$ and PM_{10} (Dhaka, 2010).

	Total Emissions (tons/year)	Top Measures	Reduction Potential (tons/year)	Costs (MEuro/ year)	Costs (Euro/ton saved)
$PM_{2.5}$	35000	Residential-Commercial: Cooking stoves - Fuelwood direct - Biomass stove improved	8600	.6170	72.0
		Industry: Other combustion, pulverized-Hard coal, grade 2- Electrostatic precipitator: 2 fields - industrial combustion	490	.0310	63.0
		Ind. Process: Cement production-No fuel use-Cyclone - - industrial process	2970	.0008	0.3
PM_{10}	45000	Residential-Commercial: Cooking stoves - Fuelwood direct - Biomass stove improved	8900	.6170	69.0
		Industry: Other combustion, pulverized-Hard coal, grade 2- Electrostatic precipitator: 2 fields - industrial combustion	1850	.0310	17.0
		Ind. Process: Cement production-No fuel use-Cyclone - - industrial process	6860	.0008	0.1

The high reduction potential for these top three measures for PM is fairly impressive, as they are able to reduce up to 1/3 of the total PM emissions at a relatively low costs/ton. It is unfortunate that mitigation controls (and related costs) were not available for SO_2, NO_X and GHGs. Without this information for GHGs, co-benefits for co-controls were not able to be realized – thus ultimately undermining the purpose and goals of the GAINS model.

It is also interesting to compare Dhaka sectoral emissions to other South Asian cities known for high pollution levels (Figure 43, using $PM_{2.5}$ for 2010 as an example). As previously discussed, it is evident here that Dhaka has a much smaller proportion of $PM_{2.5}$ emissions from the transport sector in comparison to the other representative cities, and Delhi seems to have a more typical ratio between the sectors for a mega-city, in comparison to Dhaka and Bangkok.

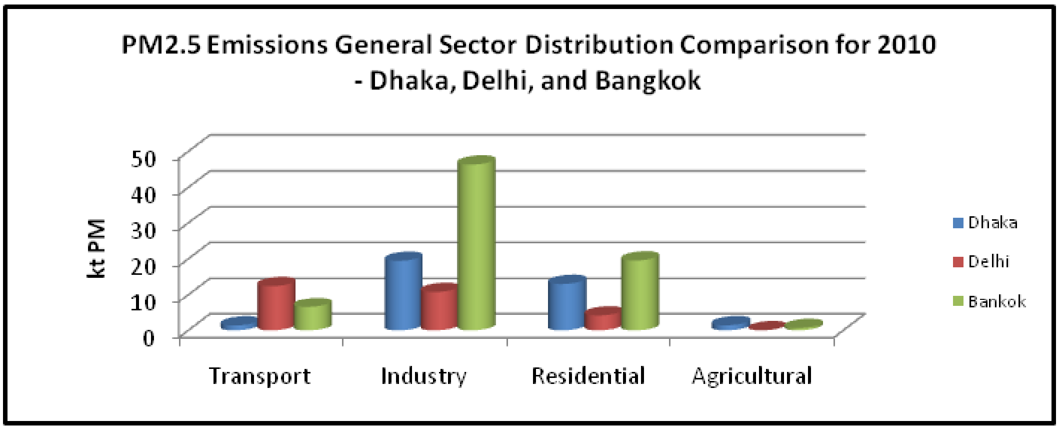


Figure 43: $PM_{2.5}$ emissions and general sector distribution for Dhaka, Delhi, and Bangkok (2010) using GAINS model.

Some recommendations are given based on this assessment for Dhaka:

- It should be considered to perform an assessment using GAINS at the beginning of each international air pollutant/GHG emission inventory related project in order to establish a general baseline based on a top-down emission analysis for the city/area of interest.
- It should be considered to use GAINS for evaluating potential available emission control measures and related costs for the city/area of interest.
- Collaboration with IIASA should be encouraged in order for the development of GAINS scenarios to produce specific analysis of components/GHGs, controls, and associated costs for an area over time.

Some critical remarks about GAINS data and the user interface:

- Some activities have very weak descriptions, such as "no fuel use" activity and "area of activity".
- Some control measures have very confusing and over-specific descriptions.
- Missing control measures for GHGs and other components is highly unfortunate.
- Very weak (health) impacts section; needs to be further developed.

At this level GAINS can be seen as a useful top-down emission estimate tool. GAINS is a good first emission inventory tool, because it is difficult to compile data in developing countries such as Bangladesh due to poor reporting procedures, lack of centralized data clearinghouses, and reduced amount of electronic information. GAINS modelling data can be valuable to fill gaps in studies (such as for bottom-up emissions inventories, source apportionments, health impact assessments, etc.), and/or to use the modelling data as a gauge where data received is of questionable quality. However, without the inclusion of GHG controls/costs, it is unfortunately not possible to begin co-benefit/co-control analysis.

5 References

Gurjar, B.R., Butler, T.M., Lawrence, M.G., Lelieveld, J. (2008) Evaluation of emissions and air quality in megacities. *Atmos. Environ., 42,* 1593-1606.

IIASA (2008) *GAINS Asia*: A scientific tool to combat air pollution and climate change simultaneously. Laxenburg, International Institute for Applied Systems Analysis.
URL: http://www.iiasa.ac.at/rains/reports/Asia/gainsbrochure_web.pdf

IIASA (2009) GAINS Online: Tutorial for advanced users. Laxenburg, International Institute for Applied Systems Analysis.
URL: http://www.iiasa.ac.at/rains/reports/GAINS-tutorial.pdf

Randall, S., Sivertsen, B., Schneider, P., Dam, V.T., Nasiruddin, M., Biswas, W., Saroar, G., Rana, M. (2011) Bangladesh Air Pollution Management Project (BAPMAN). Ambient air pollution screening study in Dhaka: 31 January - 15 February 2011. Kjeller (NILU OR 28/2011). In press.

Sivertsen, B. (2010) Integrated approaches using local air quality assessment in GHG abatement strategies. Presented at Better Air Quality Conference, Singapore, 8-11 November 2010. Kjeller (NILU F 66/2010).

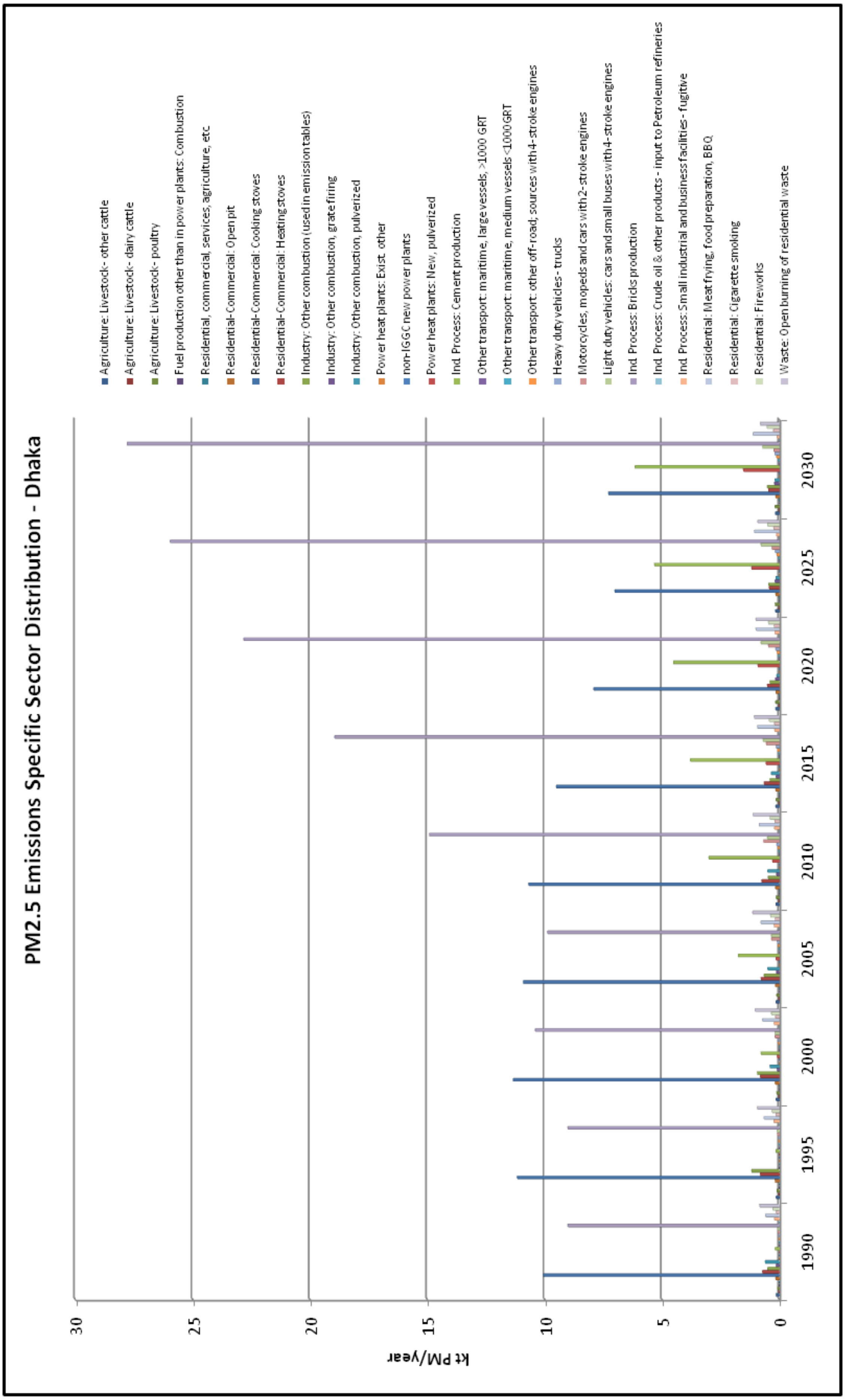
Wadud, Z., Kahn, T. (2011) CNG conversion of motor vehicles in dhaka: valuation of the co-benefits. In: *TRB 90th Annual Meeting Compendium of Papers DVD.* Washington DC,
Transportation Research Board. Paper #11-2764.
URL: http://trid.trb.org/view.aspx?id=1092656

WHO (2009) Country profiles of environmental burden of disease: Bangladesh. Geneva, World Health Organization.
URL: http://www.who.int/quantifying_ehimpacts/national/countryprofile/bangladesh.pdf

WRI (2005) World greenhouse gas emissions in 2005. Washington, DC World Resources Insititute.
URL: http://www.wri.org/chart/world-greenhouse-gas-emissions-2005

Appendix A

Specific sector distributions of $PM_{2.5}$ emissions from 1990-2030 for Dhaka


PM2.5 Emissions Specific Sector Distribution - Dhaka
kt PM/year
0
5
10
15
20
25
30
1990
1995
2000
2005
2010
2015
2020
2025
2030
Agriculture: Livestock - other cattle
Agriculture: Livestock - dairy cattle
Agriculture: Livestock - poultry
Fuel production other than in power plants: Combustion
Residential, commercial, services, agriculture, etc
Residential-Commercial: Open pit
Residential-Commercial: Cooking stoves
Residential-Commercial: Heating stoves
Industry: Other combustion (used in emission tables)
Industry: Other combustion, grate firing
Industry: Other combustion, pulverized
Power heat plants: Exist. other
non-IGGC new power plants
Power heat plants: New, pulverized
Ind. Process: Cement production
Other transport: maritime, large vessels, >1000 GRT
Other transport: maritime, medium vessels <1000GRT
Other transport: other off-road; sources with 4-stroke engines
Heavy duty vehicles - trucks
Motorcycles, mopeds and cars with 2-stroke engines
Light duty vehicles: cars and small buses with 4-stroke engines
Ind. Process: Bricks production
Ind. Process: Crude oil & other products - input to Petroleum refineries
Ind. Process: Small industrial and business facilities - fugitive
Residential: Meat frying, food preparation, BBQ
Residential: Cigarette smoking
Residential: Fireworks
Waste: Open burning of residential waste

Appendix B

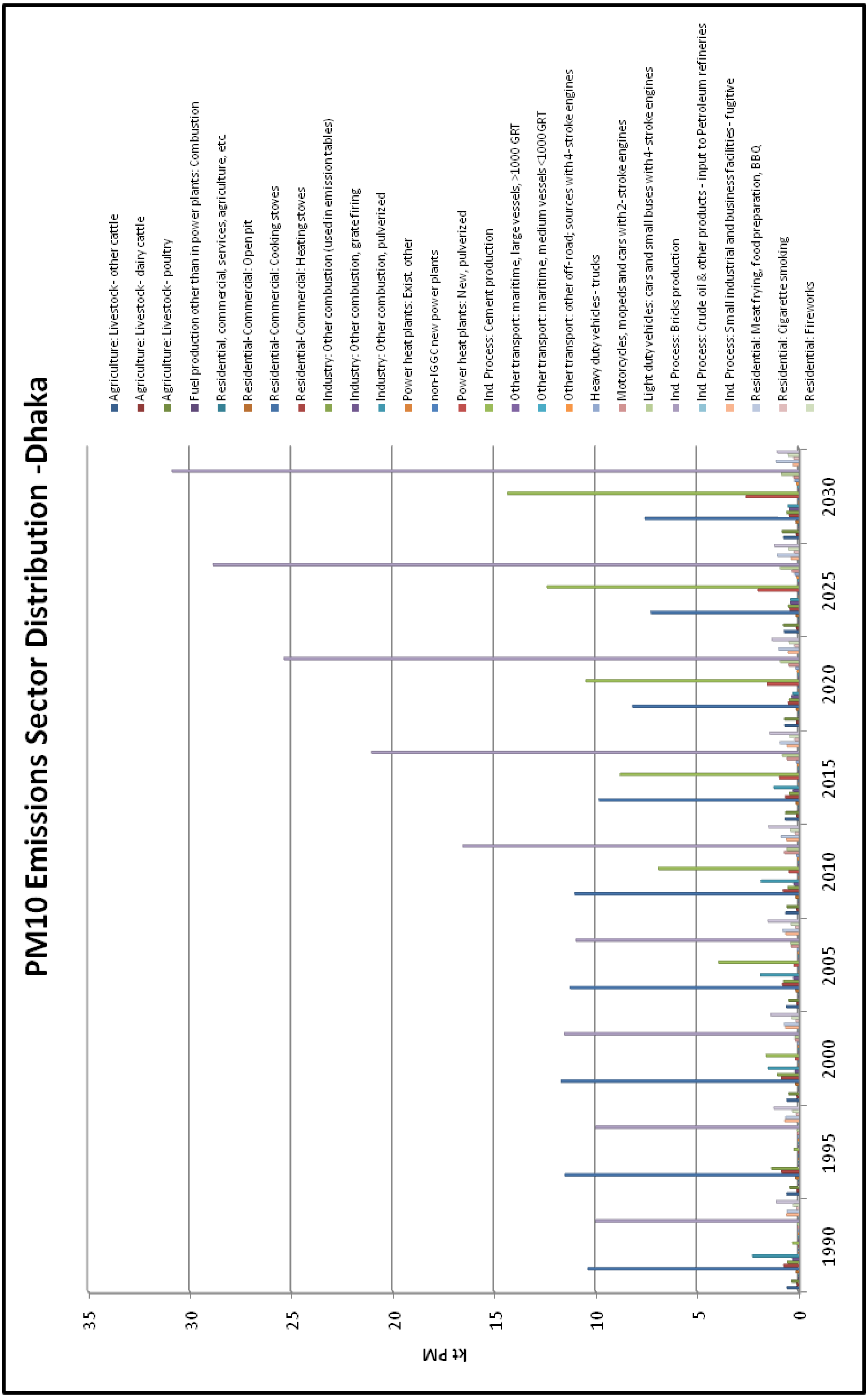
Description of Control Measure Abbreviations for $PM_{2.5}$

Abbr.	Sector-Activity-Technology
DOM-MD-GHDOM-[PJ]	Residential, commercial, services, agriculture, etc.-Medium distillates (diesel, light fuel oil)-Good housekeeping: domestic oil boilers-[10^15 Joules]
DOM_STOVE_C-FWD-STV_IMP_B-[PJ]	Residential-Commercial: Cooking stoves-Fuelwood direct-Biomass stove improved-[10^15 Joules]
DOM_STOVE_C-HC2-STV_IMP_C-[PJ]	Residential-Commercial: Cooking stoves-Hard coal, grade 2-Coal stove improved -[10^15 Joules]
DOM_STOVE_H-FWD-STV_IMP_B-[PJ]	Residential-Commercial: Heating stoves-Fuelwood direct-Biomass stove improved-[10^15 Joules]
DOM_STOVE_H-HC2-STV_IMP_C-[PJ]	Residential-Commercial: Heating stoves-Hard coal, grade 2-Coal stove improved -[10^15 Joules]
IN_OC-HF-GHIND-[PJ]	Industry: Other combustion (used in emission tables)-Heavy fuel oil-Good housekeeping: industrial oil boilers-[10^15 Joules]
IN_OC-MD-GHIND-[PJ]	Industry: Other combustion (used in emission tables)-Medium distillates (diesel, light fuel oil)-Good housekeeping: industrial oil boilers-[10^15 Joules]
IN_OC-OS1-IN_ESP1-[PJ]	Industry: Other combustion (used in emission tables)-Biomass fuels-Electrostatic precipitator: 1 field - industrial combustion-[10^15 Joules]
IN_OC1-HC2-IN_CYC-[PJ]	Industry: Other combustion, grate firing-Hard coal, grade 2-Cyclone - industrial combustion-[10^15 Joules]
IN_OC1-HC2-IN_ESP1-[PJ]	Industry: Other combustion, grate firing-Hard coal, grade 2-Electrostatic precipitator: 1 field - industrial combustion-[10^15 Joules]
IN_OC3-HC2-IN_ESP1-[PJ]	Industry: Other combustion, pulverized-Hard coal, grade 2-Electrostatic precipitator: 1 field - industrial combustion-[10^15 Joules]
IN_OC3-HC2-IN_ESP2-[PJ]	Industry: Other combustion, pulverized-Hard coal, grade 2-Electrostatic precipitator: 2 fields - industrial combustion-[10^15 Joules]

PP_NEW-HF-GHIND-[PJ]	**non-IGGC new power plants-Heavy fuel oil-Good housekeeping: industrial oil boilers-[10^15 Joules]**
PP_NEW3-HC2-ESP2-[PJ]	**Power heat plants: New, pulverized-Hard coal, grade 2-Electrostatic precipitator: 2 fields - power plants-[10^15 Joules]**
PR_CEM-NOF-PR_CYC-[Mt]	**Ind. Process: Cement production-No fuel use-Cyclone - - industrial process-[Mt]**
PR_CEM-NOF-PR_ESP1-[Mt]	**Ind. Process: Cement production-No fuel use-Electrostatic precipitator: 1 field - industrial processes-[Mt]**
PR_CEM-NOF-PR_ESP2-[Mt]	**Ind. Process: Cement production-No fuel use-Electrostatic precipitator: 2 fields - industrial processes-[Mt]**
PR_REF-NOF-PR_ESP1-[Mt]	**Ind. Process: Crude oil & other products - input to Petroleum refineries-No fuel use-Electrostatic precipitator: 1 field - industrial processes-[Mt]**
PR_REF-NOF-PR_ESP2-[Mt]	**Ind. Process: Crude oil & other products - input to Petroleum refineries-No fuel use-Electrostatic precipitator: 2 fields - industrial processes-[Mt]**
PR_SMIND_F-NOF-PRF_GP1-[M people]	**Ind. Process: Small industrial and business facilities - fugitive-No fuel use-Good practice: ind.process - stage 1 (fugitive)-[M people]**
PR_SMIND_F-NOF-PRF_GP2-[M people]	**Ind. Process: Small industrial and business facilities - fugitive-No fuel use-Good practice: ind.process - stage 2 (fugitive)-[M people]**

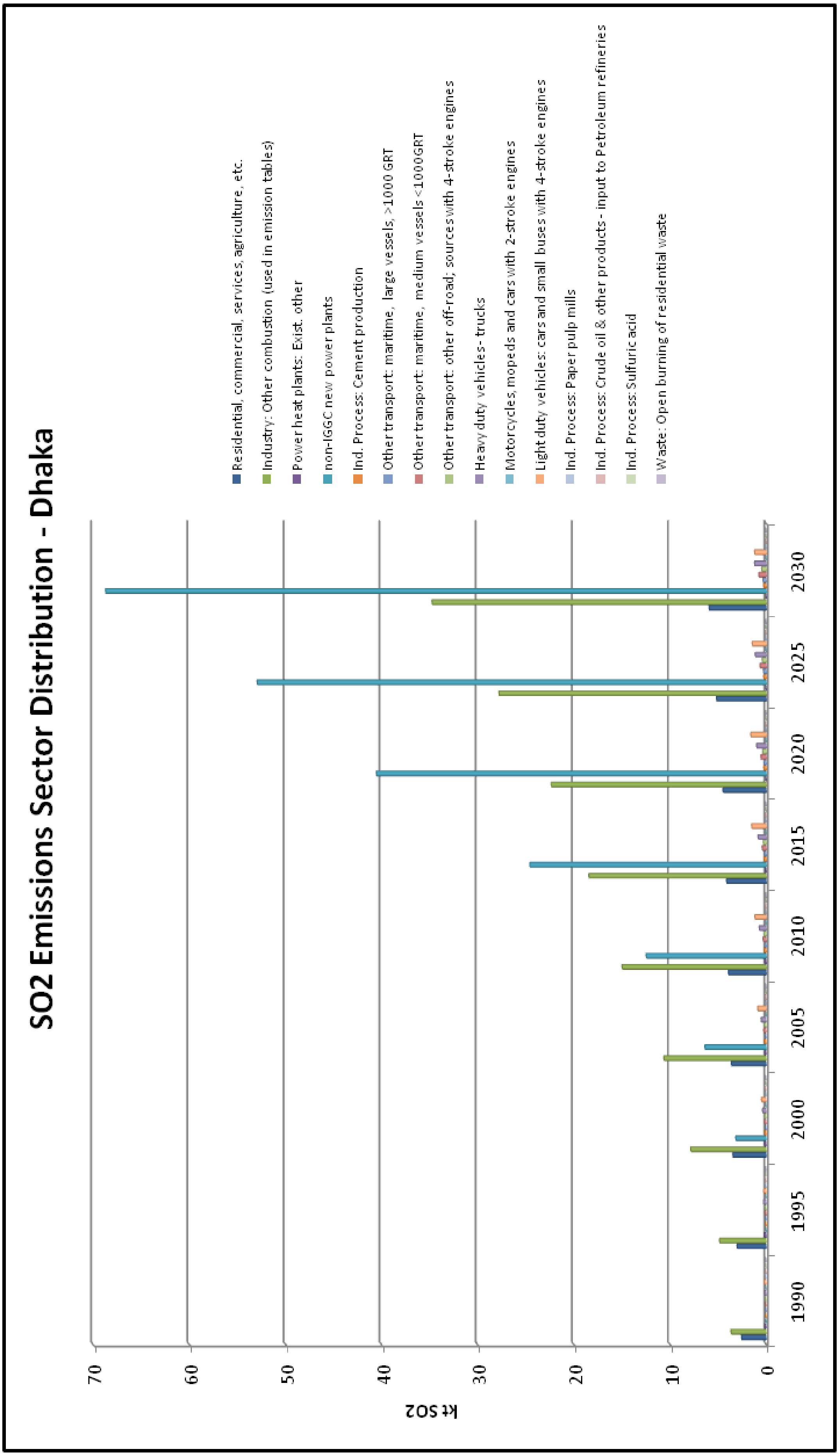
Appendix C

Specific sector distributions of PM10 emissions from 1990-2030 for Dhaka


PM10 Emissions Sector Distribution -Dhaka
kt PM
0
5
10
15
20
25
30
35
1990
1995
2000
2005
2010
2015
2020
2025
2030
Agriculture: Livestock - other cattle
Agriculture: Livestock - dairy cattle
Agriculture: Livestock - poultry
Fuel production other than in power plants: Combustion
Residential, commercial, services, agriculture, etc
Residential-Commercial: Open pit
Residential-Commercial: Cooking stoves
Residential-Commercial: Heating stoves
Industry: Other combustion (used in emission tables)
Industry: Other combustion, grate firing
Industry: Other combustion, pulverized
Power heat plants: Exist. other
non-IGGC new power plants
Power heat plants: New, pulverized
Ind. Process: Cement production
Other transport: maritime, large vessels, >1000 GRT
Other transport: maritime, medium vessels <1000 GRT
Other transport: other off-road; sources with 4-stroke engines
Heavy duty vehicles - trucks
Motorcycles, mopeds and cars with 2-stroke engines
Light duty vehicles: cars and small buses with 4-stroke engines
Ind. Process: Bricks production
Ind. Process: Crude oil & other products - input to Petroleum refineries
Ind. Process: Small industrial and business facilities - fugitive
Residential: Meat frying, food preparation, BBQ
Residential: Cigarette smoking
Residential: Fireworks

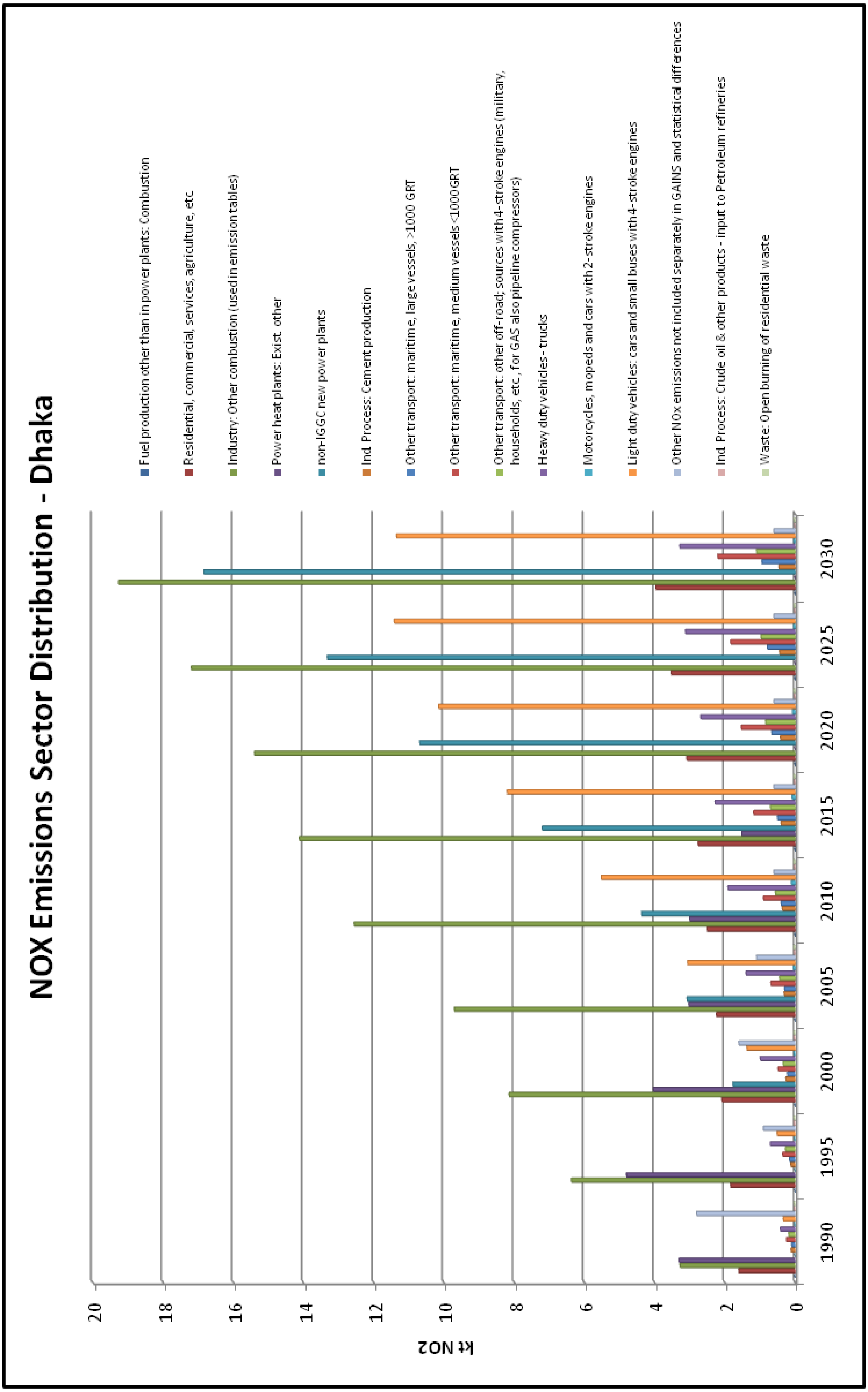
Appendix D

Specific sector distributions of SO2 emissions from 1990-2030 for Dhaka


SO2 Emissions Sector Distribution - Dhaka
kt SO2
0
10
20
30
40
50
60
70
1990
1995
2000
2005
2010
2015
2020
2025
2030
Residential, commercial, services, agriculture, etc.
Industry: Other combustion (used in emission tables)
Power heat plants: Exist. other
non-IGGC new power plants
Ind. Process: Cement production
Other transport: maritime, large vessels, >1000 GRT
Other transport: maritime, medium vessels <1000GRT
Other transport: other off-road; sources with 4-stroke engines
Heavy duty vehicles - trucks
Motorcycles, mopeds and cars with 2-stroke engines
Light duty vehicles: cars and small buses with 4-stroke engines
Ind. Process: Paper pulp mills
Ind. Process: Crude oil & other products - input to Petroleum refineries
Ind. Process: Sulfuric acid
Waste: Open burning of residential waste

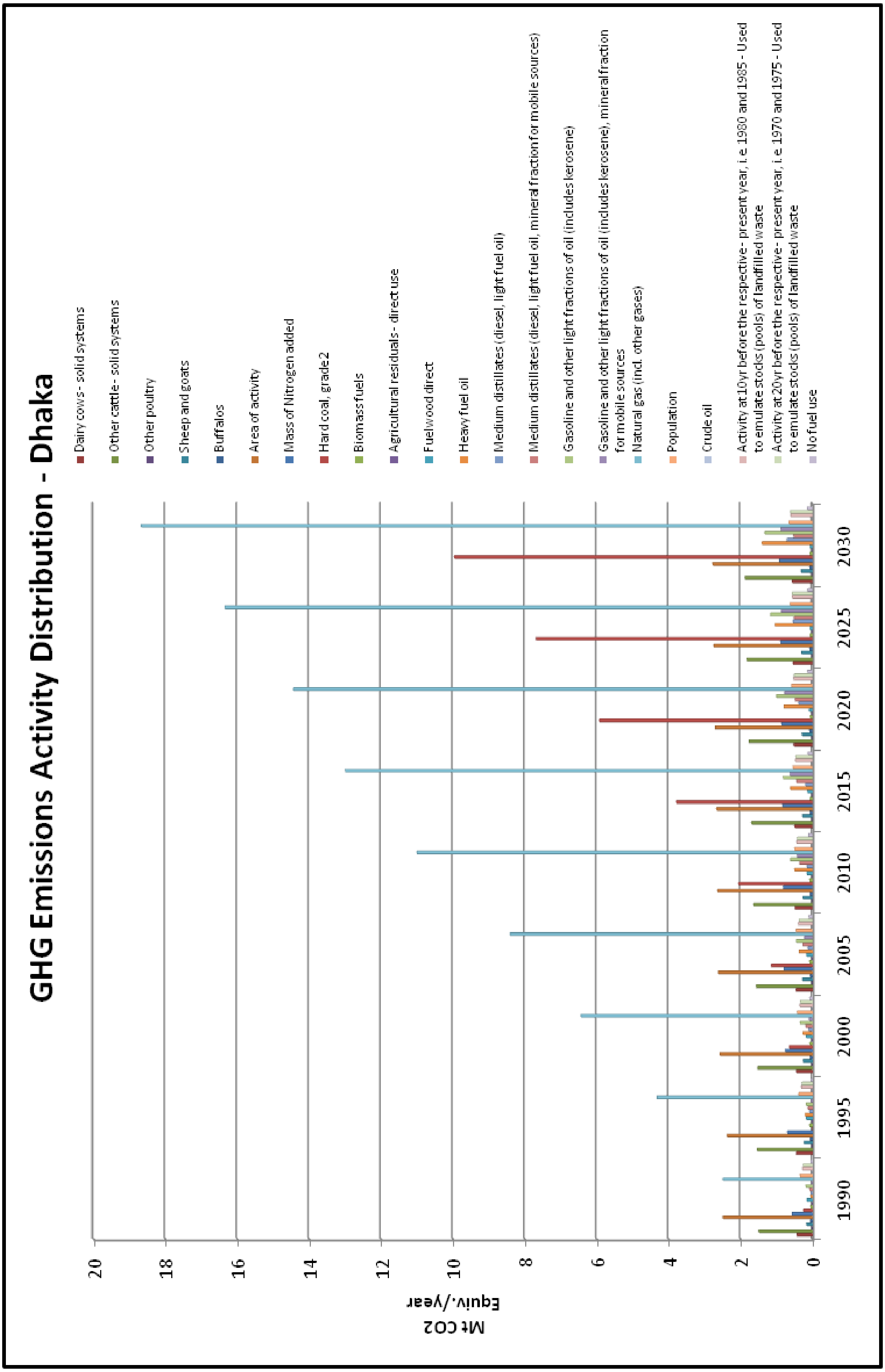
Appendix E

Specific sector distributions of NOX emissions from 1990-2030 for Dhaka


NOX Emissions Sector Distribution - Dhaka
kt NO2
0
2
4
6
8
10
12
14
16
18
20
1990
1995
2000
2005
2010
2015
2020
2025
2030
Fuel production other than in power plants: Combustion
Residential, commercial, services, agriculture, etc
Industry: Other combustion (used in emission tables)
Power heat plants: Exist. other
non-IGGC new power plants
Ind Process: Cement production
Other transport: maritime, large vessels, >1000 GRT
Other transport: maritime, medium vessels <1000 GRT
Other transport: other off-road; sources with 4-stroke engines (military, households, etc., for GAS also pipeline compressors)
Heavy duty vehicles - trucks
Motorcycles, mopeds and cars with 2-stroke engines
Light duty vehicles: cars and small buses with 4-stroke engines
Other NOx emissions not included separately in GAINS and statistical differences
Ind Process: Crude oil & other products - input to Petroleum refineries
Waste: Open burning of residential waste

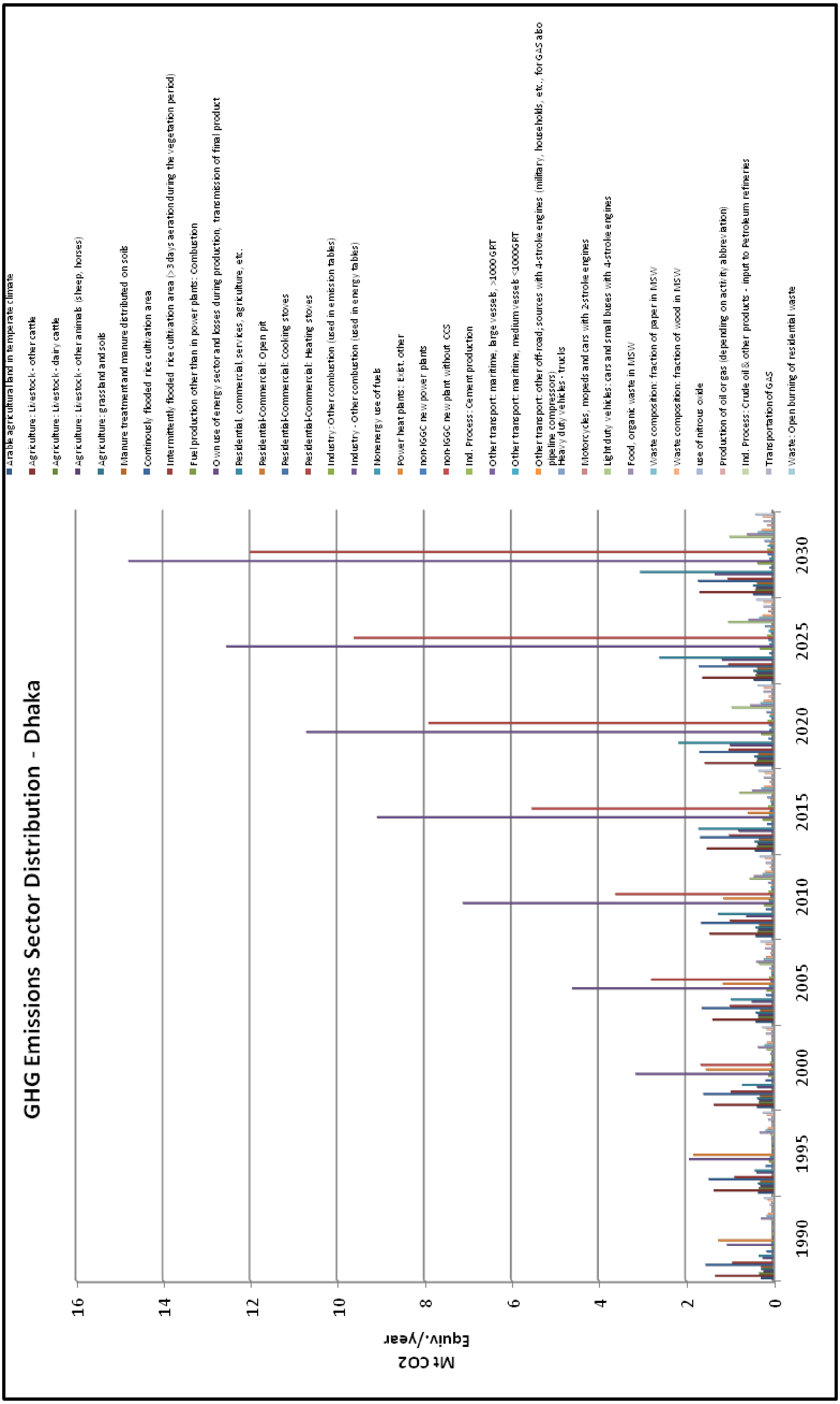
Appendix F

Activity distributions of GHG emissions from 1990-2030 for Dhaka


GHG Emissions Activity Distribution - Dhaka
Mt CO2 Equiv./year
0
2
4
6
8
10
12
14
16
18
20
1990
1995
2000
2005
2010
2015
2020
2025
2030
Dairy cows - solid systems
Other cattle - solid systems
Other poultry
Sheep and goats
Buffalos
Area of activity
Mass of Nitrogen added
Hard coal, grade 2
Biomass fuels
Agricultural residuals - direct use
Fuelwood direct
Heavy fuel oil
Medium distillates (diesel, light fuel oil)
Medium distillates (diesel, light fuel oil, mineral fraction for mobile sources)
Gasoline and other light fractions of oil (includes kerosene)
Gasoline and other light fractions of oil (includes kerosene), mineral fraction for mobile sources
Natural gas (incl. other gases)
Population
Crude oil
Activity at 10yr before the respective - present year, i.e. 1980 and 1985 - Used to emulate stocks (pools) of landfilled waste
Activity at 20yr before the respective - present year, i.e. 1970 and 1975 - Used to emulate stocks (pools) of landfilled waste
No fuel use

Appendix G

Specific sector distributions of GHG emissions from 1990-2030 for Dhaka


GHG Emissions Sector Distribution - Dhaka
Mt CO2 Equiv./year
0
2
4
6
8
10
12
14
16
1990
1995
2000
2005
2010
2015
2020
2025
2030
Arable agricultural land in temperate climate
Agriculture: Livestock - other cattle
Agriculture: Livestock - dairy cattle
Agriculture: Livestock - other animals (sheep, horses)
Agriculture: grassland and soils
Manure treatment and manure distributed on soils
Continously flooded rice cultivation area
Intermittently flooded rice cultivation area (>3 days aeration during the vegetation period)
Fuel production other than in power plants: Combustion
Own use of energy sector and losses during production, transmission of final product
Residential, commercial, services, agriculture, etc.
Residential-Commercial: Open pit
Residential-Commercial: Cooking stoves
Residential-Commercial: Heating stoves
Industry: Other combustion (used in emission tables)
Industry - Other combustion (used in energy tables)
Nonenergy use of fuels
Power heat plants: Exist. other
non-IGCC new power plants
non-IGCC new plant without CCS
Ind. Process: Cement production
Other transport: maritime, large vessels, >1000 GRT
Other transport: maritime, medium vessels <1000 GRT
Other transport: other off-road; sources with 4-stroke engines (military, households, etc., for GAS also pipeline compressors)
Heavy duty vehicles - trucks
Motorcycles, mopeds and cars with 2-stroke engines
Light duty vehicles: cars and small buses with 4-stroke engines
Food, organic waste in MSW
Waste composition: fraction of paper in MSW
Waste composition: fraction of wood in MSW
use of nitrous oxide
Production of oil or gas (depending on activity abbreviation)
Ind. Process: Crude oil & other products - input to Petroleum refineries
Transportation of GAS
Waste: Open burning of residential waste

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AUTHOR(S) Scott Randall		CLASSIFICATION * A CONTRACT REF.	
REPORT PREPARED FOR BAPMAN Project, NILU			

ABSTRACT
The city of Dhaka was chosen for this assessment due to the current ongoing project Bangladesh Air Pollution Management (BAPMAN), which concentrates mostly on the capital city Dhaka. The Greenhouse Gas and Air Pollution Interactions and Synergies model (GAINS) was used to performed this top-down assessment due to the models integrated assessment approach of capturing interactions between air pollution control and economic development, as well as its focus on presenting cost effective pollution control strategies. Results from the GAINS model assessment for Dhaka shows that for 2010 the total $PM_{2.5}$ emissions were 35000 tons/year, and the total PM_{10} emissions were 45000 tons/year. The top sectors making up the PM emissions included Industry and Residential sectors, where the specific sub-sectors were brick/cement production and residential cooking respectively; the top activities making up the emissions were “no fuel use” and “fuelwood direct”. GAINS estimates that the top 3 technical control measures available for PM can eliminate approximately 1/3 of the PM emissions at a cost of .65 MEuro/year. GAINS results also shows that for Dhaka in 2010 the total SO_2 emissions were 34000 tons/year, dominated by the Industrial sector, made up of the sub-sectors of new power plants and industrial combustion; top activities contributing to these emissions are hard coal and natural gas. NO_X emissions for Dhaka in 2010 were 30000 tons/year, dominated by the Industrial and Transport sectors, made up of the industrial combustion/power plant and light/heavy duty sub-sectors respectively; top activities contributing to these emissions include natural gas, gasoline, and medium distillates. GHG emissions for Dhaka in 2010 exceeded 23 million tons/year, dominated by the Industrial and Agricultural sectors, comprising of the industrial combustion and new power plant sub-sectors; top activities contributing to these emissions include natural gas and hard coal.

NORWEGIAN TITLE Top-down vurdering av luftforurensning og klimagasser for Dhaka, Bangladesh Analyse av data fra GAINS modellen.		
KEYWORDS Air Quality	Emissions Control	Modelling
ABSTRACT (in Norwegian)		

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B   *Restricted distribution*
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