# Estimates of Emissions from Coal Fired Thermal Power Plants in India

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## ABSTRACT

Coal is the primary fuel for electricity generation in India and its usage is continuously increasing to meet the energy demands of the country. This paper presents emissions of carbon dioxide ($CO_2$), sulfur dioxide ($SO_2$), and nitric oxide (NO) from thermal power plants in India for a period of nine years from 2001-02 to 2009-10. The emission estimates are based on a model in which the mass emission factors are theoretically calculated using the basic principles of combustion and operating conditions. Future emission scenarios for the period up to 2020-21 are generated based on the estimates of the nine years from 2001-02 to 2009-10. Power plants in India use different qualities of coal, different combustion technologies and operating conditions. As a result, these plants have differences in achieved efficiencies (coal usage per unit of electricity). The estimates show region wise differences in total emissions as well as differences in emissions per unit of electricity. Computed estimates show the total $CO_2$ emissions from thermal power plants have increased from 323474.85 Gg for the year 2001-02 to 498655.78 Gg in 2009-10. $SO_2$ emissions increased from 2519.93 Gg in 2001-02 to 3840.44 Gg in 2009-10, while NO emissions increased from 1502.07 Gg to 2314.95 Gg during this period. The emissions per unit of electricity are estimated to be in the range of 0.91 to 0.95 kg/kWh for $CO_2$, 6.94 to 7.20 g/kWh for $SO_2$, and 4.22 to 4.38 g/kWh for NO during the period 2001-02 to 2009-10. The future emission scenario, based on the projected coal consumption in Indian thermal power plants by Planning Commission of India under 'Business-as Usual (BAU)' and "Best case Scenario (BCS)' show the emission in the range of 714976 to 914680 Gg $CO_2$, 4734 to 6051 Gg $SO_2$ and 366 to 469 Gg NO in the year 2020-21. Increase in coal use efficiencies in electricity generation by thermal power plants can significantly reduce the emissions of greenhouse and polluting gases. This methodology provides a useful tool for inventory preparation in a sector where measured values for emissions factors are very sparse.

## INTRODUCTION

Emissions of greenhouse gases and other pollutants are increasing in India with the increasing demand for electricity. The aspiration for rapid economic growth leading to rapid industrialization coupled with accelerated urbanization and mechanization of agriculture has been responsible for this increasing demand of electricity ever since the independence. The electricity consumption grew from 375.39 (billion kWh) in 2000 to 600.65 (billion kWh) in 2008 at an annual growth rate of 6.67% , while the electric power generation grew from 529.12 billion kWh in 2000 to 835.27 billion kWh at an annual growth rate of 5.78% [1](www.eia.doe.gov, 2010). Fig. 1 shows the growth of electricity generation and usage in India and China during the period 2000 to 2008 based on the EIA[1] (www.eia.doe.gov, 2010) data. Large difference between electric power generation and consumption are due to transmission and distribution losses. In India, the losses are extremely high and vary between 30 to 45%.

To ensure 'Power on Demand', India has envisioned an additional generating capacity of 100,000 MW by the year 2012. It is estimated that electricity demand outstrips supply by 7-11%. With India's population of more than a billion that is growing at an annual rate of about 2%[2] (World Bank, 2000), the gap between demand and supply of the electricity may rise further. India 's current[3] (www.powermin.nic.in – Annual Report 2008-09) electric power availability is approximately 11.1 % short of demand with peak load shortages of 11.9 %, whereas in 2000-01, power capacity was 7.8 % short of demand with peak load shortage of 13%. Percentage of the electric energy shortage and peak shortage from the period 2000-01 to 2008-09 are shown in Fig. 2.

Coal is the favorite fuel for the electricity generation in countries like India and China. Abundant supply of coal locally and sustained high prices for imported natural gas and oil make coal-fired generation of electricity more attractive economically. Coal is approximately 90% of the total fuel mix for electricity generation. Fig. 3 shows the percentage of generating capacity of all categories that includes natural gas, diesel, nuclear, hydro, and renewal energy sources like biomass power, urban & industrial waste power, and wind energy. Coal and lignite based power plants have approximately 54.42% of the total electric power generation capacity in India. However, relatively lower calorific value, coupled with high ash content and inefficient combustion technologies aggravates emission of greenhouse gases and other pollutants from India's coal and lignite based thermal power plants.

Main emissions from coal fired and lignite based thermal power plants are $CO_2$, $NO_x$, $SO_x$, and air-borne inorganic particles such as fly ash, carbonaceous material (soot), suspended particulate matter (SPM), and other trace gas species. Thermal power plants, using about 70% of total coal in India[4] (Garg et. al., 2002), are among the Large Point Sources (LPS) having significant contribution (47% each for $CO_2$ and $SO_2$) in the total LPS emissions in India.

Only limited efforts[5] (Chakraborty et al., 2008) have been made so far for measuring the plant specific emissions of different gases and particulate matter in India to generate plant specific emission factors. These measurements were taken at few small plants of less than 250 MW capacities. For preparing the national green house gas (GHG) emission inventories from electricity generation in Indian thermal power plants, default emission factors prescribed by the Intergovernmental Panel on Climate Change (IPCC)[6] [IPCC, 1996] have so far been used along with the country specific net calorific values (NCV) of Indian coal types[7] (INCCA, 2010). Earlier electric power generation from thermal power plants was estimated to have contributed about 96% of total carbon dioxide ($CO_2$) emissions during 1990[8] (ALGAS ,1998) while in 1994, it was estimated about 62% [9](NATCOM, 2004) and in 2007, it has been estimated about 69% of the total $CO_2$-equivalent emissions from energy sector[7] (INCCA, 2010). The differences between 1990 estimates and 1994 and 2007 estimates also capture the different methodological approaches followed in these sets of estimates. The IPCC default emission factors, used in Indian inventory estimation, represents the average of available emission values using the similar fuel and technical processes under similar national circumstances and do not account for Indian coal characteristics or the operating conditions at the various thermal power plants in India.

A time series of emission trends of $CO_2$, $NO_x$, and $SO_x$ from the Indian coal fired and lignite based thermal power plants over a decade (2001-02 to 2009-10) is presented here. Eighty six power plants with total installed capacity of 77682 MW are considered in this analysis for which required input data was available from Central Electricity Authority of India[10] (CEA). These plants represent about 76% of the total installed capacity of thermal power plants in India. As of March 2010, there are 105 thermal power plants in India of more than 100 MW capacity each, with total installed generation capacity of 93772 MW. As per the CEA (www.cea.nic.in, 2011), public sector thermal power plants have total installed capacity of about 87592 MW while the private sector has a total installed capacity of about 14962 MW which include captive thermal power plants of less than 100 MW installed capacity. The combustion technology in these 86 plants is based on pulverized coal burning but the type of furnace technology, design of the boiler, forced draught fans etc. differ with plants. Based on the CEA data (www.cea.nic.in 2010), specific coal usage at three plants is less than 0.6 kg/kWh, at 19 plants, usage is between 0.6-07 kg/kWh, thirty nine plants use coal between 0.7-0.8 kg/kWh, fifteen plants use between 0.8-0.9 kg/kWh, seven plants use between 0.9-1.0 kg/kWh, and at three plants coal usage exceeds 1.0 kg/kWh. Hence the efficiency of the plants and the coal usage per unit of electricity generation also differ at each plant.

There is a need to modernize India's thermal power plants and reduce the coal usage per unit of electricity generation (kg/kWh). Modernization with reduction in coal usage (kg/kWh) will help in reducing the national emissions. Quality of Indian coal will remain same but with the improvement in combustion technologies, emissions can be reduced. It is estimated that 1% to 2% increase in heat rate improvements leading to efficiency improvement will result in 1% to 2% decrease in emissions per unit of electricity[11] (USAID/TVA/NTPC 2000).

Here, the emission factors for each of the 86 plants are computed based on the basic principles of coal combustion, characteristics of the coal used in different thermal power plants, and the operating conditions in these plants. This methodology provides a `bottom-up' approach for the development of emission inventory. This is the first study where emission inventory of $CO_2$, $SO_2$, and NO are developed specifically for coal fired thermal power plants in India based on the characteristic of coal and operating conditions prevalent at the plant.

## METHODOLOGY

The combustion process of the pulverized coal in the boiler is a complicated non-linear phenomenon. The pollutants emitted from thermal power plants depend largely upon the characteristics of the fuel burned, temperature of the furnace, actual air used, and any additional devices to control the emissions. At present, the control devices used in thermal power plants in India is electrostatic precipitator (ESP) to control the emission of fly ash (SPM). Some new plants use low $NO_x$ burners for high temperature (> 1500 K) combustion technologies and dry/wet $SO_2$ scrubber, if chimney height is less than 275 meters. Mass emission factors for $CO_2$, $SO_2$, and nitric oxide (NO) are computed based on the input data, such as chemical composition of the coal used at the power plants and the actual air used during combustion. These calculations are based on theoretical ideals and do not take account for the control devices. Indian coal generally has low sulfur contents. The operative combustion temperature is assumed to be 1200 K.

### Carbon Dioxide and Sulfur Dioxide

From the elemental analysis of the coal, the percentage of carbon, hydrogen, nitrogen, oxygen, ash, and moisture in the coal is known. Let C be the mass of the carbon, S of the sulfur, H of the hydrogen, $O_2$ of the oxygen, and $N_2$ of the nitrogen, then

Oxygen ($O_r$) required to burn one kilogram (kg) of coal =

$O_r = C*(32/12) + H*(16/2) + S*(32/32) - O_2$ (1)

Air mass required for $O_r$ kg of oxygen = ( $O_r$ / mass fraction of $O_2$ in the air )

= $O_r / 0.233$ (2)

If E is the percentage of excess air used in the furnace to burn the coal, the air mass used =

Air (used) = $(1 + E)* O_r / 0.233$ (3)

Knowing the air mass used to burn one kg of coal, mass of $O_2$ and $N_2$ are calculated as

$O_2$ in the air used = $(1+ E)* O_r$ (4)

$N_2$ in the air used = $0.767* (1+ E)* O_r / 0.233$ (5)

Mass of $CO_2$, $SO_2$, NO, and $H_2O$ are calculated by mass balance as

$CO_2 = C*44/12$ (6)

$SO_2 = S*64/32$ (7)

$H_2O = H*18/2$ (8)

**Oxidation of Nitrogen**

Oxides of nitrogen ($NO_x$) are nitrous oxide ($N_2O$), nitric oxide (NO), and nitrogen dioxide ($NO_2$). The formation of $NO_x$ during coal combustion is a complex process involving both homogeneous and heterogeneous reactions. Most (about 90% or higher) of the $NO_x$ emitted during combustion process is in the form of NO. NO is formed by oxidation of (i) atmospheric nitrogen, known as 'thermal NO' and (ii) chemically bound nitrogen within the fuel matrix, known as 'chemical NO'. Formation of 'thermal NO' is temperature sensitive whereas formation of 'chemical NO' is insensitive to temperature and occurs on a time scale comparable to that of combustion reactions. A kinetic model is needed to describe the detailed mechanism of the formation of NO in flames and the prediction of NO concentration in combustion products. Emission of NO varies widely with boiler conditions and is generally functions of flame temperature, excess air or concentration of oxygen in the system, percentage of boiler load, nitrogen content in the coal, and rate of gas cooling. The actual mechanism, whereby atmospheric nitrogen is oxidized, goes through a complex chain of reactions initiated by oxygen atoms.

Generally accepted principal reactions[12] (Zeldovich, 1946) for 'thermal NO' formation are

$O + N_2 = NO + N$ (09)

$N + O_2 = NO + O$ (10)

$N + OH = NO + H$ (11)

A kinetic model is beyond the scope of present analysis. Present estimates give the equilibrium concentrations of NO assuming long residence time as found in large boilers. The oxidation of nitrogen is represented by the overall balance[13] (Hanby, 1994).

$N_2 + O_2 \rightarrow 2NO$ (12)

A simple stoichiometric calculation gives the equilibrium NO concentration as

$\chi_{NO} = K_{10.1}(\chi_{N_2})^{0.5}(\chi_{O_2})^{0.5}$, (13)

where $\chi$ is the species concentration and K10.1 is is an equilibrium constant that depends upon the temperature of the gas. At 1200 K, $K_{10.1} = 0.00526$,[13] (Hanby, 1994).

**Characteristics of the Indian Coal**

Indian coal has the general properties of the Southern Hemisphere Gondwana coal, whose seams are inter-banded with mineral sediments. Run-of-mine coals typically have high ash content (ranging from 35–50%), high moisture content (4–20%), low sulfur content (0.2–0.7%), and low calorific values (between 2500–5000 kcal/kg, which is much less than the normal range of 5000 to 8000 kcal/kg. The calorific value of the Ohio (USA) coal is 6378 kcal/kg and that of the Long Kou (China) is 6087 kcal/kg[14] (Visuvasam et al., 2005). The design rating of a coal-fired burner in USA is at 6214 kcal/kg. The low calorific value implies more coal usage to deliver the same amount of electricity. The high ash content also leads to technical difficulties for utilizing the coal, as well as lower efficiency and higher costs for power plants. Some specific problems with the high ash content include high ash disposal requirements, corrosion of boiler walls and fouling of economizers, and high fly ash emissions.

Indian coal is classified by grades[15] (Coal Atlas of India, 1993) defined on the basis of Useful Heat Value (UHV), which is derived from the empirical relation of moisture and ash contents of coal. Indian coal is mostly of sub-bituminous rank, followed by bituminous rank and lignite (i.e. brown coal). The average net calorific value (NCV) for the Indian coal is estimated to be 19.63 tera-joules/kilo-tons[7] (INCCA, 2007). Elemental analysis of D, E, and F grade coal (personal communication from Central Institute of Mining and Fuel Research (CIMFR), Jharkhand, India) is given in Table 1A. Elemental analysis of coal used at Dadri, Rihand, Singrauli, Chandrapur, and Dahanu power plants (personal communication from National Energy Technology Laboratory, Pittsburgh, USA), elemental analysis of lignite used in Neyveli and Kutch plants (personal communication from the Neyveli Lignite Corporation, India), and elemental analysis of coal used at Kahalgaon, Simhadri, Sipat,[14] (Visuvasam et al., 2005) are given in Table 1B. Details of installed units, electricity generated and coal consumed in 2009-10 of respective thermal power plants are also included in Table 1B .

**Emissions Estimates**

The present (as on March, 2010) capacity for electricity generation from coal and lignite-based thermal power plants in India (including private and captive power plants) is 93772 MW. Based on the information from Central Electricity Authority[10] (CEA, 2010) for the 86 coal and lignite-based power plants with a total capacity of 77682.00 MW, Northern region has 22 of these plants with total generation capacity of 19164.5 (MW), Western region has 27 plants with a total of 30225.0 (MW) capacity, Southern region has 13 plants with a total of 9962.5 (MW) capacity, and the Eastern region has 24 plants with a total of 18330.0 (MW) capacity. The total capacity (77682 MW) of all the 86 plants represent about 85% of the total installed capacity in India. All these plants have different installed capacities with varying numbers of generation units of different capacities. For example, details about number of different generation units of ten power plants are provided in Table 1B. Table 2A shows the electric power generated at the 86 coal and lignite based thermal power plants in India during 2001-02 to 2009-10 for each region. The yearly rate of increase in the generated power by these power plants is approximately 4%. It has yearly variation with a slope of 2262 GWH for a linear trend. Table 2B shows the region wise specific coal consumptions in these power plants during the period 2001-01 to 2009-10 which ranged from 0.7 to 0.78 kg/kWh.

For each of these 86 power plants, the yearly data for the electricity generated and the specific coal consumption from CEA (2010) are used to estimate the yearly emissions of $CO_2$, $SO_2$, and NO from each of the power plants for the period 2001-02 to 2009-10 by the methodology stated earlier. Most of these plants use E and F grade coal. Accordingly, average values from the elemental analysis of E, F1 and F2 grade coals, as given in Table 1A are used in the estimates of emissions from the thermal power plants, except for the ten plants for which specific information was obtained as a personal communication as stated earlier. Excess air used at different power plants is also based on personal communication. Emissions from combustion of the supplementary fuels like diesel oil and furnace oil (FO), used in small quantity at the plants to boost the combustion and heat content, are not accounted in the present computations. In the thermal power plants operated by National Thermal Power Corporation (NTPC) in India, supplementary fuel consumption is 0.2 to 0.3 ml/unit of power, while in the old thermal power plants it may range from 1% to 4% of the fuel.

**Carbon dioxide Emissions**

$CO_2$ emissions are estimated based on the carbon content as obtained from the elemental analysis of the coal and the excess air used at the power plants. A small percentage of the carbon in the coal remains un-burnt due to factors, such as reactivity of the coal particles, milling, air to fuel ratio, flame turbulence, fuel residence time etc. A small portion of the un-burnt carbon goes with the fly ash (FA) and the remaining un-burnt carbon goes in the bottom ash (BA). Exact portion of un-burnt carbon can only be determined by experimental measurements. There are a few studies (Bartonova et al., 2011; Mandal, 2008; Sathyanathan and Mohammad, 2004)[16, 17, 18] to estimate un-burnt carbon in coal ash. Depending upon the combustion condition and the fuel, un-burnt carbon varies from 0.5% to 10% in FA and 2% to 30% in BA. It is difficult to get the measurement data for un-burnt carbon at each plant, and hence, this analysis is based on the available information (obtained as personal communication from the site visits of the plants). It is assumed that 10% un-burnt carbon mixes with the BA and 2% un-burnt carbon remains in the FA.

Annual $CO_2$ emissions from all the 86 coal and lignite based power plants for the years 2001-02 to 2009-10 are given in Table 3A for each region and for all India. $CO_2$ emissions are increasing at an average annual rate of 5.6% on the all India basis in these power plants during the period 2001-02 to 2009-10. Earlier, Mittal and Sharma (2003)[19] estimated total annual $CO_2$ emissions from all the coal-fired power plants in India as 395 million tons in 1997-98. These estimates were based on the installed plant capacity, since the actual electricity generation data was not available at that time. Garg and Shukla (2002)[21] have estimated emissions of 212.5 and 348 million tons of $CO_2$ for the year 1990 and 1995 respectively from electric power generation sector in India. Olivier et al. (1999)[21] have estimated 257.7 million tons of $CO_2$ emissions for the year 1990 from fossil fuel combustion in power generation in the Indian region which include India and neighboring countries. In another study[7] (INCCA, 2010), $CO_2$ emissions from electricity generation for the year 2007 are estimated as 715.83 million tons. These estimates are based on the average net calorific value of the coal used in the thermal power plants assuming coal utilization 90% of the total fuel mix. Thus the contribution of the coal in the $CO_2$ emissions will be 644 million tons. The present estimates show the $CO_2$ emissions from coal and lignite based 86 power plants during April 1, 2007 – March 31, 2008 as 455 million tons. The electric power generated by these 86 thermal power plants during 2007-08 was 476992 GWH. This is about 85% of the total electric power 558990 GWH generated in 2007-08 by thermal power plants in India. Thus, the total $CO_2$ emissions can be an estimated as about 523 million tons from all the thermal power plants in India. In these estimations, it is assumed that 12% of the carbon is lost as bottom and fly ash and are not oxidized. Present estimates are based on electric power generation where as in INCCA's report estimates are based on gross coal usage (top down approach). If the carbon lost in ash is not considered, then the present estimates of $CO_2$ emissions from 86 power plants will increase to 546 million tons from 455 million tons and total emissions from all the thermal power plant will increase to 677 million tons which is close to 644 million tons estimated in INCCA's report. It may be noted here that this is a "bottom-up" approach for developing emission inventory compared to "top-down" approach adopted in

INCCA report. Table 3A gives region wise $CO_2$ emissions from coal and lignite based power plants in India. $CO_2$ emissions have been rising in all the regions each year with the electric power generation except for 2005-06 when the electric power generation and $CO_2$ emissions were less compared to 2004-05 in Western and Southern region.

$CO_2$ emissions per unit of electricity from power plants are given in Table 3B**,** which shows that $CO_2$ emissions per unit of electricity range between 0.82 and 1.0 kg/kWh. These are regional average and change year to year. $CO_2$ emissions depend upon the carbon content in the coal used and the specific coal usage (plant efficiency). Some plants are more efficient than others and the plant efficiency also varies from year to year due to maintenance. In 2009-10, plant wise emissions of $CO_2$ (kg/kWh) varied from 0.58 at DCR-Yamunanagar to 1.59 at Faridabad, which is an old power plant. 48 power plants emit $CO_2$ in the range of 0.58-1.0 kg/kWh. Three plants have $CO_2$ emissions more than 1.4 kg/kWh. This number reflects operational inefficiency due to poor coal quality, operating conditions, maintenance, and/or plant design. Garg et al. (2002)[23] have estimated a national average of 1.2 kg/kWh $CO_2$ emissions from thermal power plants in India, which falls in the range of emissions presented here. Based on the measurement data carried out in 11 different generating units in different thermal power plants in India, Chowdhury et al. (2004)[22] have given an average emission factors for $CO_2$ emission as 0.998 kg/kWh (range 0.776-1.49 kg/kWh) which is also in the range of present emission factors. Chakraborty et al. (2008)[5] made on-line measurements of $CO_2$ emissions at some coal based power plants of 250 MW capacities over a period of two years during 2003-2004 and report $CO_2$ emission factors in the range of 0.852-0.969 kg/kWh.

**<u>Sulfur dioxide Emissions</u>**

$SO_2$ emissions from coal combustion mainly depends on the sulfur content in the coal unlike the emissions of $CO_2$ and NO which depends on the operating conditions and the design of the plant. Sulfur content in Indian coal is much lower compared to the coal in the United States. Table 1A and 1B gives the elemental analysis of coal used in power plants in India and shows the sulfur content as less than 0.5% compared to 1.8 % sulfur content in USA (Ohio) coal[14] (Visuvasan et al., 2005), though lignite has higher sulfur content. Acid rain by $SO_2$ emissions is presently not observed but may become a problem in future with increasing use or blending of Indian coal with imported coal of higher sulfur content. Power plant combustors operate at temperatures usually around 1200 K. These temperatures are above the thermal decomposition temperature of calcium sulfate, it does not serve as a sulfur retaining agent. The small amount of sulfur found in power plant coal ash is of no practical significance in reducing $SO_2$ emissions to the atmosphere[23] (Rees et al., 1966). Hence in these estimates all the sulfur in the coal is considered to have been converted to $SO_2$. Table 4A shows the region wise estimates of $SO_2$ emissions from thermal power plants in India assuming that no control technology is in use.

Annual $SO_2$ emissions have increased from 2.5 million tons in 2001 to 3.8 million tons in 2009 at an average annual rate of 169.39 thousand tons per year. Lignite fuel has higher sulfur content and hence Western region and the Southern region which have lignite based power plants show higher $SO_2$ emissions. As given in Table 4B, region wise $SO_2$ emission per unit of electricity varies between 5.77 g/kWh and 9.38 g/kWh. National average varies between 7.02 and 7.34 g/kWh compare to 7.0 g/kWh estimated by Garg et al. (2002) for the year1995. Plant wise variation of $SO_2$ emissions per unit of electricity in 2009-10 is estimated between 2.72 and 13 g/kWh in coal based plants and 32.85 g/kWh at lignite based plants. In 2009, Kutch, Giral, Surat, and Akrimopa plants have been estimated to emit $SO_2$ at the rate of 33 g/kWh and Neyveli plant at the rate of 23 g/kWh. For coal based thermal power plants, these estimate show that Chandrapur has $SO_2$ emission per unit of electricity at the rate of 13 g/kWh followed by Faridabad at the rate of 10.6 g/kWh, and 7.74 g/kWh at Satpura in 2009-10. Garg et al.

(2002) found Satpura thermal power plant to be the highest emitter of $SO_2$ among the non-lignite based thermal power plants in the year 1995. Beside these seven plants, $SO_2$ emissions in six plants have the range 2.7-5 g/kWh, 15 plants have the range of 5-6 g/kWh, and 36 plants have the range of 6-7 g /kWh, while 22 plants have the range of 7-9 g /kWh. The national average based on the 86 power plants is 8.04 g/kWh. Chowdhury et al. (2004)[24] have given an average emission factors for $SO_2$ emission as 8.7 g/ kWh (range 5.21-15.99 g/ kWh). Chakraborty et al. (2008)[5] measured $SO_2$ emissions in the range of 7.445-8.763 g/kWh for plants of the 250 MW capacities.

**Emissions of oxides of Nitrogen**

The formation of NO is influenced by the concentration of oxygen (which depends on the excess air) in the system and the flame temperature. NO emissions are estimated based on equilibrium reaction calculated at an average gas temperature of 1200 K. This is a theoretical ideal. In reality the gas temperature in the boiler varies from 1000 K to 2500 K and the reaction also occurs in several phases. The estimates take into account the excess air used at the individual power plants. These estimates may be of limited value in describing details of NO formation but useful in establishing a baseline for NO emissions.

All India and region wise estimates of annual NO emissions are given in Table 5A. These estimates show that annual NO emissions in India have increased from 1.5 million tons in 2001-02 to2.3 million tons in 2009-10 at an average annual rate of 5.65 per cent. The Eastern region has the lowest NO emissions and the electricity generation while the Western region has the highest NO emissions and the electricity generation. Annual NO emission per unit of generated electricity are given in Table 5B. These estimates show average NO emissions in the range of 4.2-4.4 g/kWh over the nine year period of 2001-02 to 2009-10 for all India. Region wise it varies between 3.68 and 5.0 g/kWh.

In 2009, plant wise NO emissions are estimated to vary between 2.13 g/kWh at the Kahalgaon plant to 8.18 g/kWh at the Faridabad Plant. There were 8 plants where NO emissions were between 2.0 and 3.0 g/kWh, 12 plants between 3.0 and 4.0 g/kWh, 26 plants between 4.0 and 5.0 g/kWh, 30 plants between 5.0 and 6.0 g/kWh, and 9 plants between 6.0 and 7.0 g/kWh. Chowdhury et al. (2004) have given an average emission factor for NO emission as 2.42 g/ kWh (range 1.54-3.263 g/kWh). Chakraborty et al. (2008) measured NO emissions in the range of 1.81-2.37 g/kWh for plants of the 250 MW capacities.

**Results and Discussions**

Emissions from thermal power plants are influenced by many factors. $CO_2$ and $SO_2$ emissions are influenced by the chemical composition (particularly carbon and sulfur content) of coal and the coal usage per unit of electricity. NO emissions are influenced by the excess air used during combustion and the coal usage. Emissions from the ten power plants as given in Table 1 B for which coal analyses and plant characteristics were available are analyzed. Total emissions from these plants for 2009-10 are given in Table 6 and emissions per unit of electricity are shown in Figure 4. As Kutch plant uses lignite with 2.25% sulfur, it is estimated to emit about 33 g/kWh $SO_2$, whereas Kahalgaon plant emits only 2.72 g/kWh $SO_2$ as the sulfur content in the coal used at this plant is only 0.17%. NO emissions per unit of electricity are lowest (< 3.0 g/kWh) at Chandrapur, Dahanu, and Kahalgaon plants, whereas at Singrauli NO emissions are about 5 g/kWh and $CO_2$ emissions are about 1.12 (kg/kWh) as the Singrauli coal has 50.2 % carbon. Dadri, Chandrapur, and Dahanu plants emit about 0.82, 1.02, and 0.85 kg/kWh respectively, as these plants use high carbon content coals. There are wide variations in emissions at different plants due to coal quality, specific coal usage, and use of excess air.

'Compounded Annual Growth Rate (CAGR)' during 2001-02 to 2009-10 of $CO_2$ emissions from thermal power plants is estimated to be 4.9 %, of electricity generation and $SO_2$ emissions as 4.7 %, and of NO emissions as 4.9%. Garg and Shukla (2002) have observed a 'Compounded Annual Growth Rate (CAGR)' of 10.3% in the $CO_2$ emissions during 1990-1995 from electric power generation sector in India. It shows that CAGR has come down in this decade.

Coal combustion in power plants is a complex phenomenon. Formation of the heat and other by-products like pollutant gases go through many complex non-linear processes. Present analysis gives theoretical estimates of emissions of $CO_2$, $SO_2$, and NO based on ideal conditions. Assumptions involved in these estimates introduce many uncertainties including the non-availability of the exact input data. Due to differences in assumptions, some discrepancies are expected between present estimates and measurements or emissions based on IPP's emission factors.

**Emission Trends**

Two scenarios are generated for future emission trends. (1) PC-BAU scenario is based on coal consumption projected by Planning Commission of India in 2020 for thermal power generation under business-as-usual (BAU) scenario (scheme 1); and (2) PC-BCS scenario is based on future coal consumption projection for thermal power generation in India in 2020 by Planning Commission of India under best case scenario (BCS) (scheme 2). Under BCS, the electricity generation from coal and lignite based power plants will taper off to approximately 650000 GWH while under PC-BAU scenario, electric power generation from coal and lignite based power plants will continue to grow and is expected to rise as 950000 GWH by the year 2020-21(Fig. 5). Nuclear and other sources of energy are expected to share the fuel usage for electricity generation under BCS scenario besides better efficiencies. $CO_2$ emission trends for the two scenarios are shown in Fig.6. With PC-BAU scenario, $CO_2$ emissions are expected to rise up to 850,000 Gg by 2020-21, while with PC-BCS scenario, these emissions will rise to only 700,00 Gg by 2020-21. Under scenario (1), $SO_2$ emissions will rise to 6000 Gg, and under scenario (2) it is projected to rise to 4500 Gg only (Fig.7). Projections for NO emissions by 2020 are, 475, and 350 Gg respectively (Fig. 8). Projections for 2020 for electricity generation and emissions of $CO_2$ , SO2 and NO are lower in BCS (Scheme 2) scenarios because of assumption of application of better technologies and improvement in energy efficiencies in generation units.

## CONCLUSIONS

This study provides a viable "bottom-up" (i.e. plant wise) methodology for the development of emission inventory of different trace atmospheric species from coal combustion in thermal power plants in India for which measured emission factors are still sparse. Thermal power plants vary widely in design and operating conditions and hence it is relatively cumbersome to develop plant specific emission factors by measurements. There is a wide diversity between plants for coal usage (kg/kWh), coal quality, and the operating conditions. Hence there are large differences in emission factors (g/kWh) of $CO_2$, $SO_2$, and NO as shown earlier. This is the first study which gives the emissions from 86 operational thermal power plants with future trends nationally.

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**KEY WORDS**

Emission Inventories

Coal Combustions

Thermal Power Plants

Carbon dioxide

**Acknowledgements**: Authors sincerely thank the referee for providing very useful and thoughtful suggestions. C. Sharma and R. Singh are grateful to the Director NPL and the Head, RASD for their support

**Table 1A**: Elemental analysis, moisture content**,** and grades of typical Indian coals

| Coal grade | C% | H% | S% | $N_2$% | $O_2$% | A% | M% | NCV (Kcal/kg) |
|---|---|---|---|---|---|---|---|---|
| D | 33.1 | 2.46 | 0.44 | 0.83 | NA | 25.9 | 7.2 | 4999.0 |
| D | 30 | 2.48 | 0.57 | 0.69 | NA | 27.1 | 2.9 | 5555.0 |
| D | 32.31 | 2.12 | 0.4 | 0.78 | NA | 25 | 7.3 | 5068.0 |
| E | 37.9 | 2.4 | 0.53 | 0.8 | 6% | 30.4 | 7.5 | 4529.0 |
| F1 | 41.87 | 3.33 | 0.56 | 0.94 | 6% | 34.07 | 7.8 | 4137.0 |
| F2 | 44.47 | 3.37 | 0.35 | 0.99 | 6% | 36.3 | 8.4 | 3833.0 |
| Average of E and F2 | 41.19 | 2.89 | 0.44 | 0.9 | 0.06 | 33.35 | 7.95 | 4182.0 |

**Table 1B**: Plant characteristics and elemental analysis of the coal/ lignite used at ten thermal power plants

| TPS | **Plant Characterization** | | | | **Elemental Analysis** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Numbers of Units and generation capacities | Electricity Generation (million units) | Coal Consumption (000T) | **Excess air (%)** | C (%) | H (%) | S (%) | N2 (%) | O2 (%) | A (%) |
| Dadri | 4*210 + 2*490 | 7828.20 | 4931.80 | 25 | 40.30 | 4.16 | 0.50 | 0.90 | 15.92 | 38.22 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Rihand | 4*500 | 16743.40 | 10715.80 | 25 | 37.70 | 3.26 | 0.39 | 0.73 | 14.65 | 43.23 |
| Singrauli | 5*200 + 2*500 | 16264.40 | 11222.50 | 20 | 50.20 | 4.78 | 0.33 | 1.09 | 17.25 | 26.33 |
| Chandrapur | 4*210 + 3*500 | 14622.90 | 12283.30 | 10 | 37.70 | 2.66 | 0.80 | 1.07 | 5.78 | 47.00 |
| Dahanu | 2*250 | 4481.90 | 2868.420 | 10 | 42.40 | 3.73 | 0.39 | 0.82 | 14.21 | 38.46 |
| Neyveli (lignite) | 6*50 + 3*100 + 2*210 +7*210 | 19449.10 | 14781.30 | 25 | 26.10 | 2.33 | 1.50 | 0.24 | 16.33 | 7.00 |
| Kutch (lignite) | 2*70 + 2*75 | 1209.40 | 882.90 | 25 | 28.30 | 3.03 | 2.25 | 0.88 | 13.94 | 15.00 |
| Kahalgaon | 4*210 + 3*500 | 11311.00 | 9048.80 | 10 | 25.10 | 2.95 | 0.17 | 0.50 | 6.71 | 46.00 |
| Simhadri | 2*500 | 8520.70 | 6390.52 | 25 | 29.00 | 1.88 | 0.25 | 0.52 | 6.96 | 46.00 |
| Sipat | 2*500 | 8175.00 | 6196.65 | 25 | 30.70 | 2.30 | 0.40 | 0.60 | 5.35 | 45.0 |

**Table 2A**: Region wise electric power generation (GWH) from coal and lignite based power plants in India during 2001-02 to 2009-10

| Year | Region | | | | |
|---|---|---|---|---|---|
| | Northern | Western | Southern | Eastern | All India |
| 2001-02 | 96840.69 | 118177.46 | 79544.73 | 55844.52 | 350407.40 |
| 2002-03 | 99186.65 | 127808.16 | 88889.47 | 58627.34 | 374511.62 |
| 2003-04 | 102598.48 | 124190.00 | 93811.00 | 66077.63 | 386677.11 |
| 2004-05 | 105217.00 | 128034.45 | 95280.00 | 73416.89 | 401948.34 |
| 2005-06 | 110640.84 | 125784.62 | 92410.48 | 85223.63 | 414059.39 |
| 2006-07 | 120850.93 | 132027.93 | 98828.33 | 92748.22 | 444455.41 |
| 2007-08 | 126563.76 | 153705.86 | 101392.39 | 95330.46 | 476992.47 |
| 2008-09 | 132479.53 | 169537.66 | 107282.38 | 99663.67 | 508963.24 |
| 2009-10 | 136919.98 | 177289.84 | 114193.64 | 104709.98 | 533113.44 |

**Table 2B**: Region wise specific coal consumption (kg/kWh) during 2001-02 to 2009-10

| Year | Northern | Western | Southern | Eastern |
|---|---|---|---|---|
| 2001-02 | 0.74 | 0.72 | 0.75 | 0.76 |

| | | | | |
|---|---|---|---|---|
| 2002-03 | 0.75 | 0.7 | 0.74 | 0.77 |
| 2003-04 | 0.75 | 0.71 | 0.7 | 0.78 |
| 2004-05 | 0.76 | 0.72 | 0.7 | 0.77 |
| 2005-06 | 0.77 | 0.74 | 0.7 | 0.75 |
| 2006-07 | 0.76 | 0.72 | 0.71 | 0.76 |
| 2007-08 | 0.76 | 0.77 | 0.74 | 0.75 |
| 2008-09 | 0.76 | 0.77 | 0.74 | 0.75 |
| 2009-10 | 0.76 | 0.77 | 0.74 | 0.75 |

**Table 3A**: Region wise $CO_2$ emissions from thermal power plants in India (Gg) during 2001-02 to 2009-10

| Year | Region | | | | |
|---|---|---|---|---|---|
| | Northern | Western | Southern | Eastern | All India |
| 2001-02 | 89704.89 | 109796.74 | 71134.90 | 52838.33 | 323474.85 |
| 2002-03 | 93165.88 | 116728.55 | 78587.62 | 56000.77 | 344482.83 |
| 2003-04 | 102371.06 | 116817.91 | 77032.98 | 66264.89 | 362486.84 |
| 2004-05 | 99915.90 | 122452.03 | 78511.49 | 73157.09 | 374036.51 |
| 2005-06 | 104038.33 | 119666.63 | 76152.41 | 78400.36 | 378257.73 |
| 2006-07 | 118752.49 | 127870.66 | 82755.09 | 87848.35 | 417226.59 |
| 2007-08 | 120947.31 | 153831.83 | 89031.37 | 91272.11 | 455082.62 |
| 2008-09 | 124185.42 | 169576.14 | 93626.06 | 94165.38 | 481553.00 |
| 2009-10 | 127763.21 | 173415.44 | 99547.80 | 97929.32 | 498655.78 |

**Table 3B**: Region wise $CO_2$ emissions per unit of electricity generation (kg/kWh) during 2001-02 to 009-10

| Year | Region | | | | |
|---|---|---|---|---|---|
| | Northern | Western | Southern | Eastern | All India |

| | | | | | |
|---|---|---|---|---|---|
| 2001-02 | 0.93 | 0.93 | 0.89 | 0.95 | 0.92 |
| 2002-03 | 0.94 | 0.91 | 0.88 | 0.96 | 0.92 |
| 2003-04 | 1.00 | 0.94 | 0.82 | 1.00 | 0.94 |
| 2004-05 | 0.95 | 0.96 | 0.82 | 1.00 | 0.93 |
| 2005-06 | 0.94 | 0.95 | 0.82 | 0.92 | 0.91 |
| 2006-07 | 0.98 | 0.97 | 0.84 | 0.95 | 0.94 |
| 2007-08 | 0.96 | 1.00 | 0.88 | 0.96 | 0.95 |
| 2008-09 | 0.94 | 1.00 | 0.87 | 0.94 | 0.95 |
| 2009-10 | 0.93 | 0.98 | 0.87 | 0.94 | 0.94 |

**Table 4A**: Region wise $SO_2$ emissions (Gg) during 2001-02 to 2009-10

| Year | Region | | | | |
|---|---|---|---|---|---|
| | Northern | Western | Southern | Eastern | India |
| 2001-02 | 558.85 | 873.55 | 745.74 | 341.79 | 2519.93 |
| 2002-03 | 579.01 | 915.25 | 774.32 | 361.94 | 2630.52 |
| 2003-04 | 643.27 | 918.21 | 782.97 | 428.09 | 2772.54 |
| 2004-05 | 623.81 | 952.22 | 803.65 | 473.56 | 2853.24 |
| 2005-06 | 650.25 | 916.95 | 800.00 | 507.66 | 2874.86 |
| 2006-07 | 748.97 | 1022.69 | 834.56 | 570.21 | 3176.43 |
| 2007-08 | 758.25 | 1243.12 | 906.36 | 593.67 | 3501.41 |
| 2008-09 | 780.51 | 1336.77 | 937.95 | 608.76 | 3663.99 |
| 2009-10 | 822.54 | 1374.66 | 1012.53 | 630.71 | 3840.44 |

**Table 4B**: Region wise $SO_2$ emissions per unit of electricity generation (g/kWh) during 2001-02 to 2009-10

| Year | Region | |
|---|---|---|

| | Northern | Western | Southern | Eastern | India |
|---|---|---|---|---|---|
| 2001-02 | 558.85 | 873.55 | 745.74 | 341.79 | 2519.93 |
| 2002-03 | 579.01 | 915.25 | 774.32 | 361.94 | 2630.52 |
| 2003-04 | 643.27 | 918.21 | 782.97 | 428.09 | 2772.54 |
| 2004-05 | 623.81 | 952.22 | 803.65 | 473.56 | 2853.24 |
| 2005-06 | 650.25 | 916.95 | 800.00 | 507.66 | 2874.86 |
| 2006-07 | 748.97 | 1022.69 | 834.56 | 570.21 | 3176.43 |
| 2007-08 | 758.25 | 1243.12 | 906.36 | 593.67 | 3501.41 |
| 2008-09 | 780.51 | 1336.77 | 937.95 | 608.76 | 3663.99 |
| 2009-10 | 822.54 | 1374.66 | 1012.53 | 630.71 | 3840.44 |

**Table 5A**: Region wise NO emissions (Gg) during 2001-02 to 2009-10

| | Northern | Western | Southern | Eastern | India |
|---|---|---|---|---|---|
| 2001-02 | 447.05 | 510.06 | 332.86 | 212,10 | 1502.07 |
| 2002-03 | 464.52 | 543.33 | 369.05 | 224.35 | 1601.25 |
| 2003-04 | 511.53 | 541.42 | 361.46 | 262.01 | 1676.42 |
| 2004-05 | 499.13 | 567.06 | 366.9 | 284.46 | 1717.56 |
| 2005-06 | 523.38 | 564.68 | 349.23 | 306.49 | 1743.78 |
| 2006-07 | 594.73 | 628.77 | 383.24 | 341.29 | 1948.03 |
| 2007-08 | 603.75 | 720.07 | 413.11 | 352.09 | 2089.02 |
| 2008-09 | 620.69 | 772.89 | 423.17 | 374.16 | 2190.91 |
| 2009-10 | 639.75 | 820.95 | 464.85 | 389.14 | 2314.95 |

**Table 5B**: Region wise NO emissions per unit of electricity generation (g/kWh) during 2001-02 to 2009-10

| Year | Region | | | | |
|---|---|---|---|---|---|
| | Northern | Western | Southern | Eastern | India |
| 2001-02 | 4.62 | 4.32 | 4.19 | 3.8 | 4.29 |
| 2002-03 | 4.68 | 4.25 | 4.15 | 3.83 | 4.28 |
| 2003-04 | 5.0 | 4.36 | 3.85 | 3.97 | 4.34 |
| 2004-05 | 4.74 | 4.43 | 3.85 | 3.88 | 4.27 |
| 2005-06 | 4.73 | 4.43 | 3.8 | 3.6 | 4.22 |
| 2006-07 | 4.92 | 4.78 | 3.88 | 3.68 | 4.39 |
| 2007-08 | 4.78 | 4.69 | 4.07 | 3.69 | 4.38 |
| 2008-09 | 4.69 | 4.56 | 3.94 | 3.75 | 4.34 |
| 2009-10 | 4.67 | 4.64 | 4.07 | 3.72 | 4.34 |

**Table 6**: Emissions at ten Indian thermal power plants in 2009-10

| S. No. | Thermal Power Plant | $CO_2$ (Thousand ton) | $SO_2$ (kg) | NO (kg) |
|---|---|---|---|---|
| 1 | Dadri | 6413.07 | 49.32 | 33.08 |
| 2 | Rihand | 13049.07 | 83.58 | 64.49 |
| 3 | Singrauli | 18185.23 | 74.07 | 81.71 |
| 4 | Sipat | 6142.32 | 49.57 | 31.62 |
| 5 | Kutch lignite | 807.08 | 39.73 | 4.16 |
| 6 | Chandrapur | 14938.09 | 196.53 | 41.68 |
| 7 | Dahanu | 3812.31 | 22.37 | 11.75 |
| 8 | Kahalgaon | 7319.83 | 30.77 | 24.11 |
| 9 | Simhadri | 5979.83 | 31.95 | 29.29 |
| 10 | Neyveli lignite | 12443.43 | 443.44 | 58.02 |

**Figure 1.** Growth of electricity generation and consumption in India and China

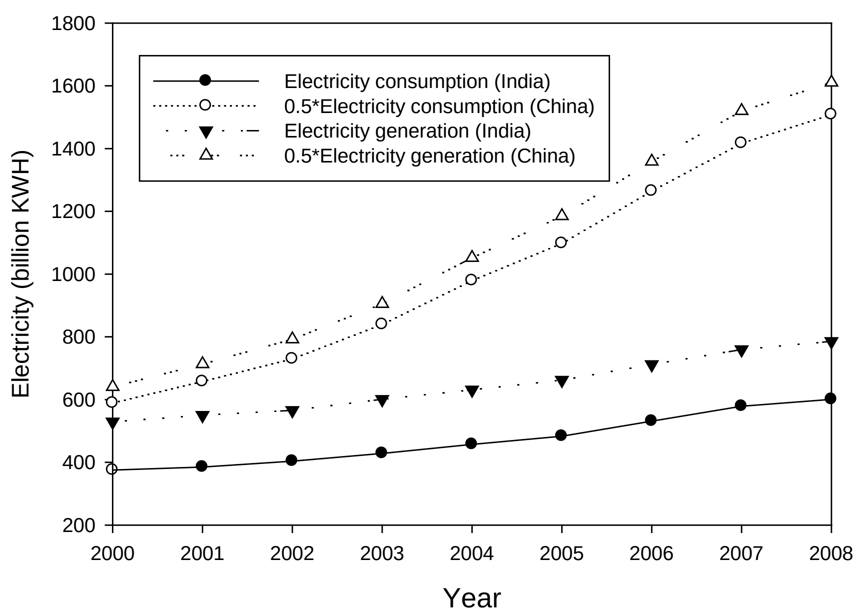



**Figure 2.** Trend of energy and peak shortage in India (%)

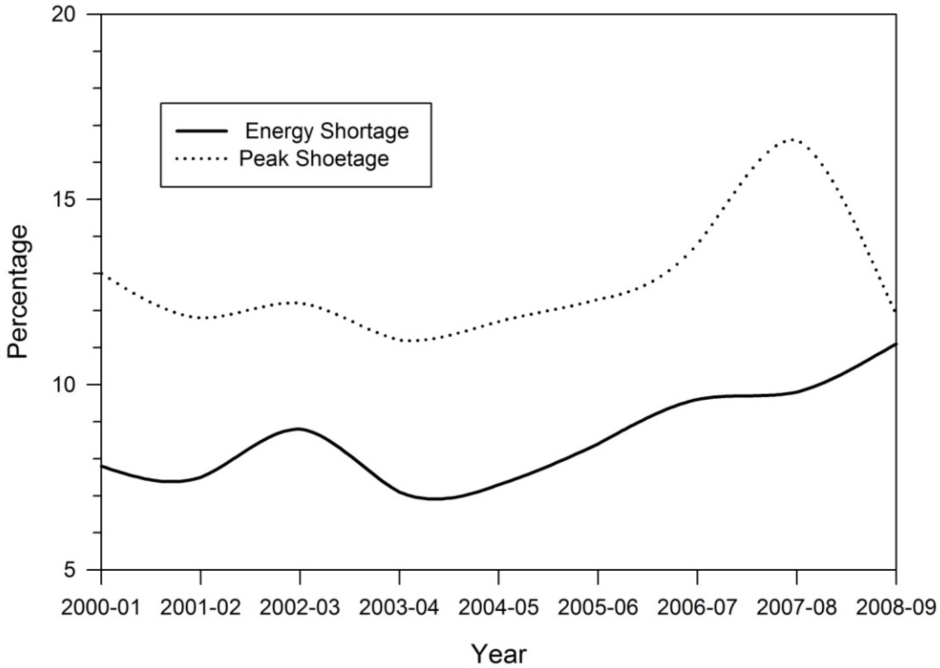



**Figure 3.** Fuel percentage used in the electricity generation as on December 31, 2010

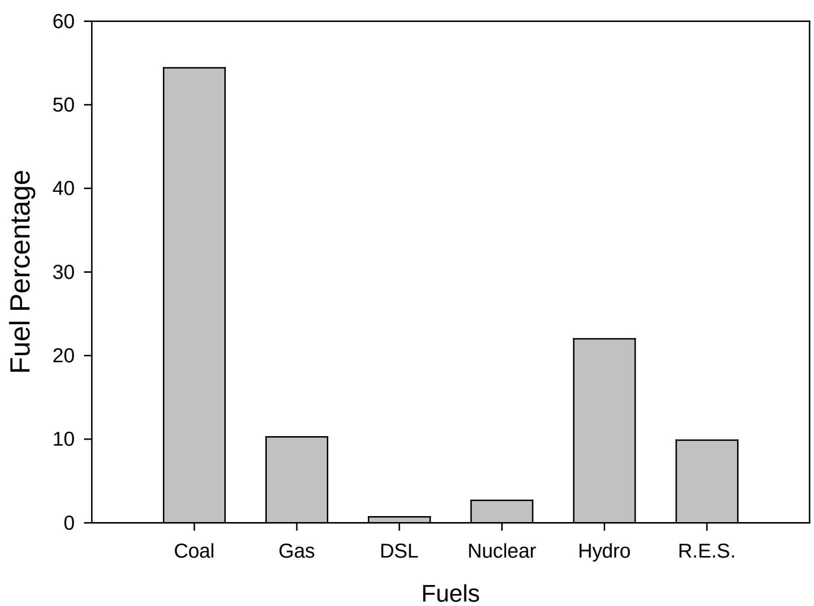



**Figure 4.** Emission factors of $CO_2$, $SO_2$ and NO in ten Indian thermal power stations

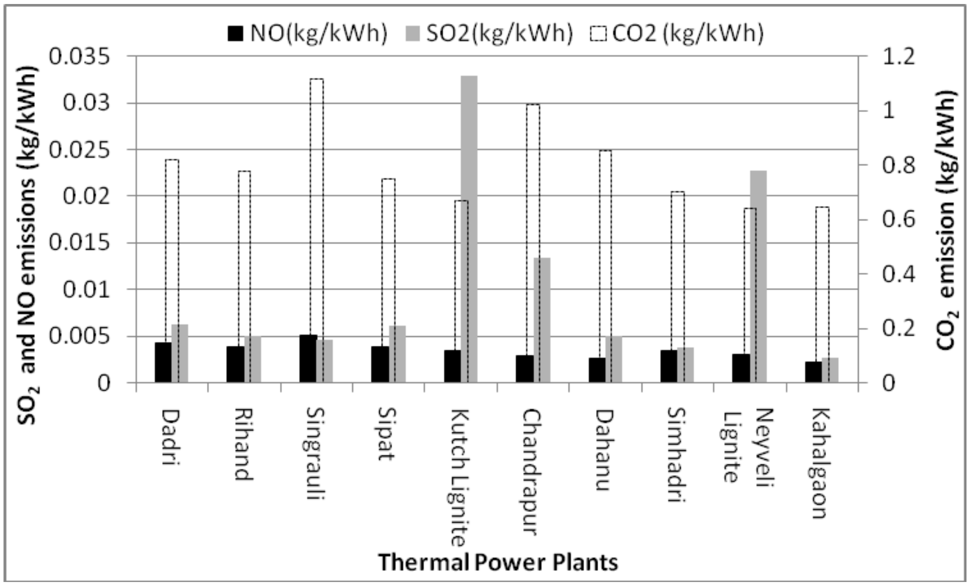



**Figure 5.** Scenarios of electricity generation from coal based thermal power plants in India

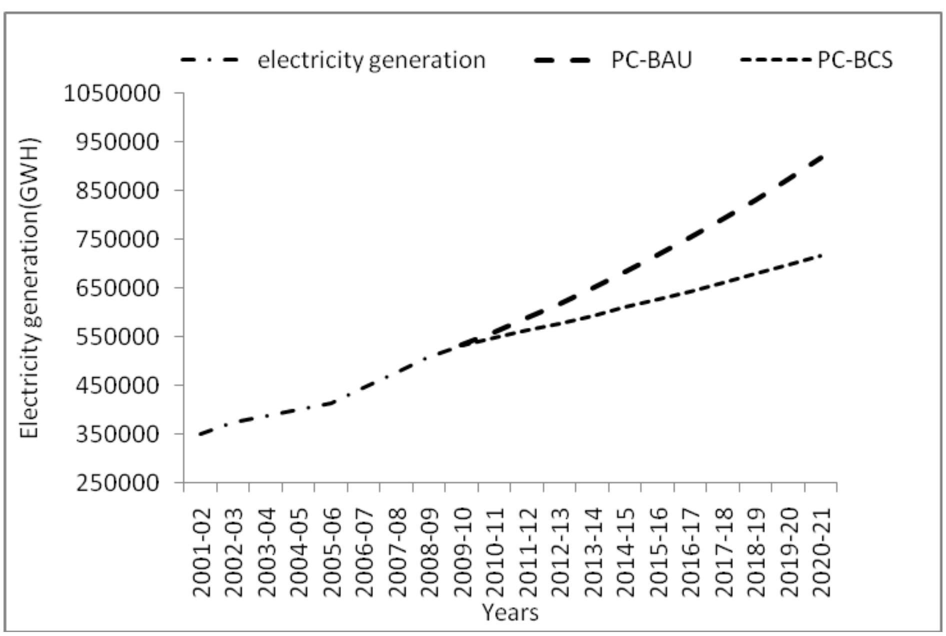


**Figure 6.** Scenarios of $CO_2$ emissions from coal based thermal power plants in India

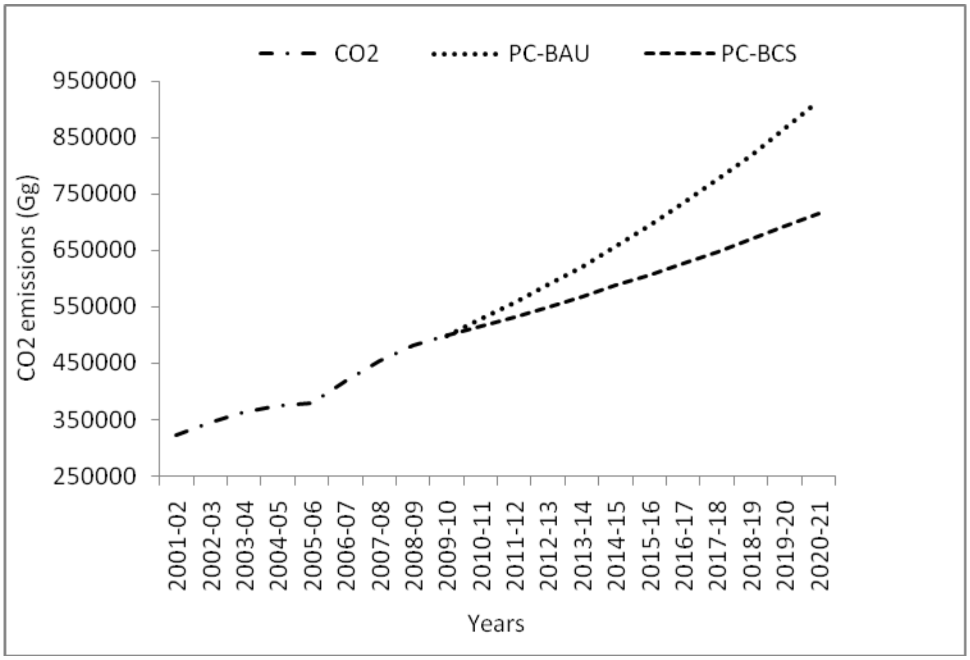



**Figure 7.** Scenarios of $SO_2$ emissions from coal based thermal power plants in India

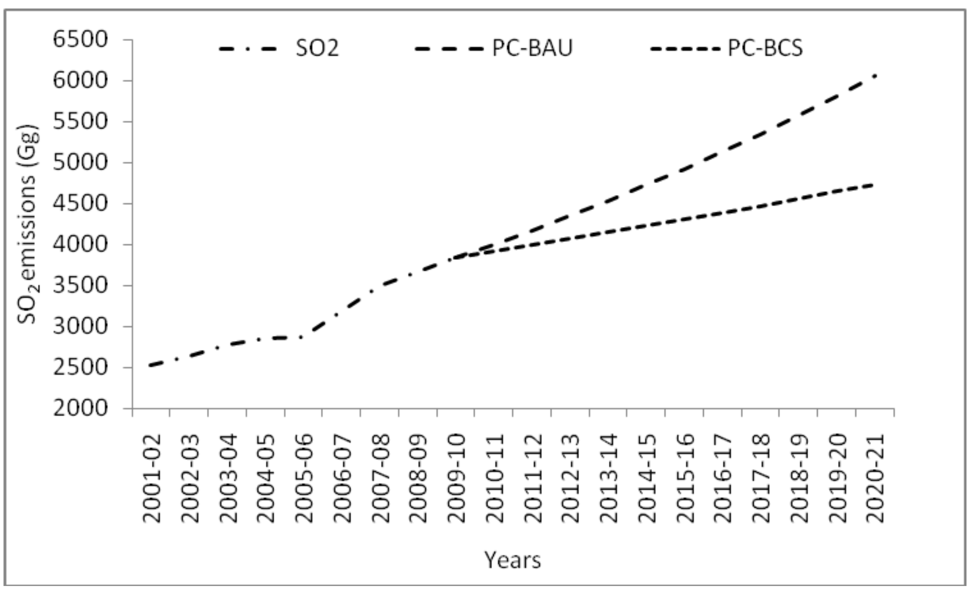
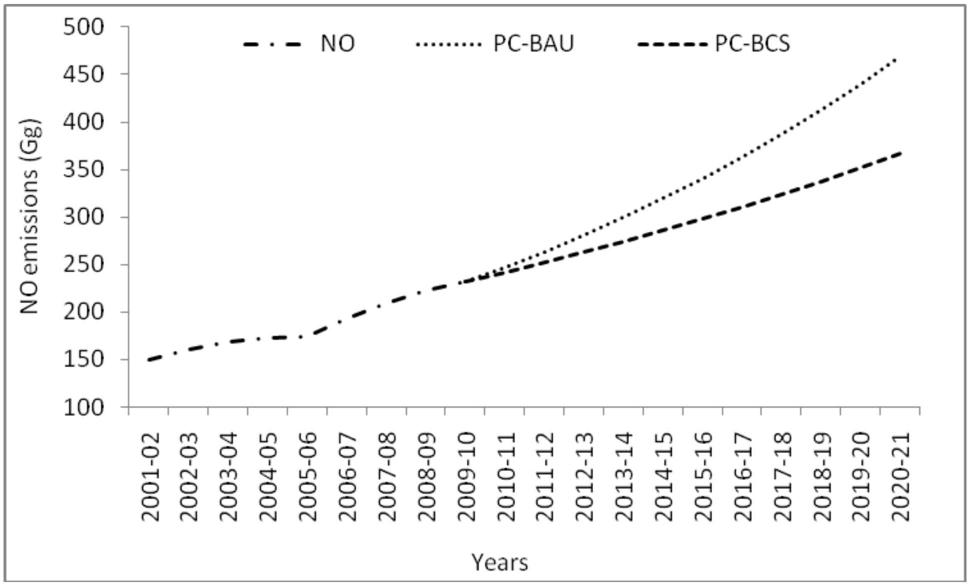



**Figure 8.** Scenarios of NO emissions from coal based thermal power plants in India


500
450
400
350
300
250
200
150
100
NO emissions (Gg)
NO
PC-BAU
PC-BCS
2001-02
2002-03
2003-04
2004-05
2005-06
2006-07
2007-08
2008-09
2009-10
2010-11
2011-12
2012-13
2013-14
2014-15
2015-16
2016-17
2017-18
2018-19
2019-20
2020-21
Years