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ORIGINAL PAPER

Formulation, application and evaluation of a stack emission model for coal-based power stations

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Abstract Estimation of coal power plant emissions is a vital step to visualise emission trends with respect to specific policy implementations and technological interventions so that their effectiveness in terms of emission reductions and ambient air quality improvement can be quantitatively assessed. However, research work concerning stack emission estimations specifically for coal power plants in India is limited. To bridge the present gap, we present a plant-specific multi-year and multi-parameter Coal Power Stack Emission Model. This model has been developed to explore current and historical annual stack emissions from a coal-based thermal power plant taking into account essential variables such as coal characteristics, process attributes and control equipment aspects, which can significantly influence the stack emissions. This study concentrates on development of Coal Power Stack Emission model and its application for the estimation of plant and year-specific emission factors and stack emissions for a coal-based power plant at Badarpur, New Delhi, for the period of 2000–2008. The validation of Coal Power Stack Emission model has also been successfully carried out by comparing the trends of percentage change in annual emission estimates and observed ambient air concentrations of total suspended particles, PM_{10} and sulphur dioxide at two nearby air quality monitoring stations, namely Siri Fort and Nizamuddin.

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Introduction

Air quality concern has been one of the prime environmental issues for the Indian government and public alike for past few decades. The Ministry of Environment and Forests (MoEF), Government of India, has been taking appropriate policy decisions so as to reduce near- and long-term air pollution emissions and consequences. Power sector is a major contributor to air pollution emissions, particularly that of particulate matter (PM) and sulphur dioxide (SO_2). According to MoP (Ministry of Power) (2011) the all India installed power generation capacity as on December 31, 2010 was about 169749 MW comprising of ~111034 MW thermal (~65 %), ~36367 MW hydro (22 %), 4560 MW nuclear (~3 %) and ~16787 MW renewable (~10 %), which clearly indicates the dominance of thermal power. Coal is expected to dominate the thermal power sector consumption (presently 83 % share) at least for the next three decades in India. The major reason for the dominance of coal power is the cost effectiveness of fuel than other alternative fuels like natural gas, hydropower and nuclear (Asian Development Bank (ADB) 2009).

There are several studies on estimation of emissions from different sources, but emission inventories specifically related to coal power plants in India are sparse and limited to specific pollutants. For example, Shrestha and Timilsina (1997) have estimated SO_2 emission intensities of the power sector based on fuel analysis in 12 selected Asian economies during the period 1980–1994 including India. Reddy and Venkataraman (2002) constructed for the first time a comprehensive, spatially resolved ($0.25^{\circ} \times 0.25^{\circ}$) fossil fuel consumption database and emission inventory for fossil fuel consumption in India. In this inventory, emissions of sulphur dioxide and aerosol chemical constituents were estimated for 1996–1997. Mittal and Sharma (2004), on the other hand, used stoichiometric analysis for developing emission inventories for thermal power plants in India. Raghuvanshi et al. (2006) prepared an inventory of CO_2 emissions in 2004 from the present energy generation and predicted the same for the next two decades (until 2025). Garg et al. (2006) provided multigas emission inventory of GHGs and air pollutants in India from various sources for the period of 1985–2005. Chakraborty et al. (2008) presented for the very first time emissions from thermal power plants only, which were based on online measurements carried out in a plant following the standard experimental guidelines. Ghosh (2010) aimed to analyse thermal power generation in India for the period 2004–2005 and 2007–2008 to determine net generation and specific CO_2 emissions. It has been observed that most of the studies do not include technological changes and fuel characteristics, which can greatly influence the emission estimations. Few studies have estimated stack emissions considering only selected variables and the combined effect of all concerned variables on these emissions was left untouched. Since most of the emission estimation studies in India are limited to few pollutants or greenhouse gases only, this may not provide a clear and comprehensive picture of emissions for policy making purpose. Power plant emissions have been the target for investigating the pollutant dispersion pattern using various types of air dispersion models (Kho et al., 2007; Awasthi et al., 2006). The emission model that can estimate power plant emissions could be useful as a first step in air quality modelling. But there is no such model available for stack emission estimation from coal power plants in India.

In the present study, a simple stack emission model, namely the "Coal Power Stack Emission (CPSE)" model has been developed to estimate and explore current and historical emission trends of important pollutants and GHGs like total suspended particles (TSP), PM_{10}, $PM_{2.5}$, SO_2, NO_x, CO_2 and Hg from a coal power plant. The emission estimation methodology takes into account essential variables like coal characteristics (e.g. ash content, sulphur content, mercury content, indigenous/imported coal), technological attributes (e.g. plant technology, type of turbine, sub/super critical process) and control equipment features (e.g. availability of desulphurisation, low NOx burners, catalytic reactors, Electro-Static Precipitator, bag house, age of ESP, up-gradation of ESP if any). The proposed CPSE model has been used to establish emissions from a coal-based power plant at Badarpur, New Delhi during 2000–2008. The comparison between percentage change in annual emissions and observed ambient air concentrations at nearby air quality monitoring stations has been carried out for successful validation of CPSE model.

Materials and methods

Plant-specific methodology

The plant-specific multi-year, multi-parameter CPSE model is developed using MS Excel and Visual Basic Application (VBA) to estimate current and historical annual emissions from a coal-based power plant taking into account essential variables which can be of great effect on emission levels. The CPSE model estimates annual stack emissions of particulates (e.g. TSP, PM_{10}, $PM_{2.5}$), gaseous pollutants (e.g. NO_x, SO_2), greenhouse gases (GHGs) (e.g. CO_2) and hazardous pollutants (e.g. Hg) for several years simultaneously using emission factor or fuel consumption approach. We have used fuel analysis approach instead of emission factors to estimate emissions of TSP, PM_{10}, $PM_{2.5}$, SO_2 and Hg. This has been carried out in such a way that readily and reliably available local data and correction factors are used to estimate the emissions using Eqs. (1) (3) and (5), respectively. The emission factor-based approach has been used to estimate emissions of CO_2 and NO_x using Eqs. (2) and (4), respectively.

$$E_{\mathrm{PM}_Y} = (\mathrm{CC} \times A)_y \times (1 - A_\mathrm{r}) \times \left(1 - \eta_{g,h,j,n}\right) \times D \times K \tag{1}$$

$$E_{\mathrm{NO}_x} = \mathrm{CC} \times \mathrm{EF}_{\mathrm{NO}_x,b,g} \times D \tag{2}$$

$$E_{\mathrm{SO}_2} = \mathrm{CC} \times S \times \frac{\mathrm{MW}_p}{\mathrm{MW}_f} \times (1 - S_\mathrm{r}) \times \left(1 - \eta_g\right) \tag{3}$$

$$E_{\mathrm{CO}_2} = G \times \mathrm{EF}_{\mathrm{CO}_2,f,ccs} \tag{4}$$

$$E_{H_g} = \mathrm{CC} \times H_g \times L \times \left(1 - \eta_{g,h,j}\right) \times D \tag{5}$$

where subscripts b, f, g, h, j, n, ccs and y stand for boiler type, process, emission control technology, age of electrostatic precipitator (ESP), up-gradation of ESP, low sulphur-content factor, availability of carbon capture and storage (CCS) facility and particulate size. Furthermore, CC is total coal consumption (kt), A is ash content in coal (%), A_r is fraction of ash retained, η is control efficiency (%), D is plant technology factor, K is particulate fraction by size, EF is emission factor (t/kt), S is fraction of sulphur content in coal, S_r is sulphur retained, MW_p is molecular weight of pollutant (g/mol), MW_f is molecular weight of fuel (g/mol), G is gross generation (GWh), H_g is mercury content in coal (t/kt) and L is fraction release rate of mercury.

Activity

The total coal consumption (*CC*) was computed by adding indigenous, washed and imported coal consumed in the plant as shown in Eq. (6):

$$CC = CC_i + CC_w + CC_m \tag{6}$$

where CC_i, CC_w and CC_m stand for indigenous, washed and imported coal consumed in the plant, respectively.

In case of lack of availability of coal consumption data according to coal type, total coal consumption was calculated based on gross generation and specific coal consumption in the plant suggested by Gurjar et al. (2004). These equations for calculating gross generation (G) and total coal consumption (CC) are given here as Eqs. (7) and (8):

$$G = C \times \mathrm{PLF} \times 24 \times 365 \tag{7}$$

$$\mathrm{CC} = G \times \mathrm{SPCC} \tag{8}$$

where C is derated capacity of power plant (GW), PLF is plant load factor (%) and SPCC is specific coal consumption (kt/GWh).

The total ash (CC × A), sulphur (CC × S) and mercury contents (CC × H_g) in coal were calculated by adding the products of consumption of coal (indigenous, washed and imported) and ash, sulphur and mercury content of respective type of coal as shown in Eqs (9–11).

$$(\mathrm{CC} \times A) = (\mathrm{CC_i} \times A_\mathrm{i}) + (\mathrm{CC_w} \times A_\mathrm{w}) + (\mathrm{CC_m} \times A_\mathrm{m}) \tag{9}$$

$$\mathrm{CC} \times S = (\mathrm{CC_i} \times S_\mathrm{i}) + (\mathrm{CC_w} \times S_\mathrm{w}) + (\mathrm{CC_m} \times S_\mathrm{m}) \tag{10}$$

$$\mathrm{CC} \times H_\mathrm{g} = \left(\mathrm{CC_i} \times H_{\mathrm{g_i}}\right) + \left(CC_\mathrm{w} \times H_{\mathrm{g_w}}\right) + \left(\mathrm{CC_m} \times H_{\mathrm{g_m}}\right) \tag{11}$$

where (CC_i × A_i) is total indigenous coal ash content (%), (CC_w × A_w) is total washed coal ash content (%), (CC_m × A_m) is total imported coal ash content (%), (CC_i × S_i) is total indigenous coal fraction sulphur content, (CC_w × S_w) is total washed coal fraction sulphur content, (CC_m × S_m) is total imported coal fraction sulphur content, (CC_i × H_{gi}) is total indigenous coal mercury content (t), (CC_w × H_{gw}) is total washed coal mercury content (t) and (CC_m × H_{gm}) is total imported coal mercury content (t).

Essential variables and basic emission rates

As discussed below, many researchers have studied the effects of various variables such as coal characteristics, technological attributes and control equipment aspects on coal power plant efficiency and resulting emissions.

Coal characteristics

As far as coal characteristics are considered, it is well known that less ash, sulphur and mercury content in coal leads to lesser amount of stack emissions of particulates, SO_2 and Hg, respectively. Also, percentage of ash and sulphur retained, fraction release rate of mercury and type of coal consumed (indigenous, washed or imported) are the key factors influencing their stack emissions. The CPSE model provides flexibility in selecting types of coal as indigenous, washed and imported separately and also combinations therein. The user has to fill in ash, sulphur and mercury content of coal as per type of coal burnt in the plant.

Process attributes

There are several process attributes of coal power plant that, too, influence stack emissions of various parameters, one of them being the type of the boiler, such as tangentially fired or swirl burner. The emission factor of NO_x emissions for normal firing is normally much higher as compared with tangentially fired boilers (Vijay et al., 2004). Accordingly, CPSE model uses NO_x emission factor based on selection between two types of boilers, namely tangentially fired and swirl burner which significantly influence the NO_x emissions from a coal power plant.

The plant technology also plays a key role in stack emissions of various pollutants. According to Ghosh (2011), if advanced technology like integrated gasification of combined cycle (IGCC) is used instead of Pulverized coal (PC) in coal power plants, then stack emission of particulate, NO_x and SO_2 are reduced by about 7, 20 and 16 %, respectively. Plant technology influences also the particulate fraction by size. The particulate size fraction for the said plant technology is adapted from Zhao et al. (2008) so as to estimate $PM_{2.5}$ and PM_{10} emissions. Furthermore, a study by Tian et al. (2010) reveals that the release rate of Hg stack emissions is more than 99 % provided the PC technology is used in coal power plant. Consequently, Grate, PC and IGCC are the options for coal power plant technology that are made available to users in the proposed CPSE model.

The type of the process technology (e.g. sub-critical, super-critical, ultra-supercritical or IGCC) used in a coal power plant also significantly affects CO_2 emissions. According to Rezvani et al. (2007), for example, the specific CO_2 emission for the super-critical plant is 12 % lower than the one for the sub-critical system. Beer (2007) specifies CO_2 emissions in kg/KWh for all these process technologies with and without carbon capture and storage (CCS). The CPSE model provides all these four alternatives with and without CCS to user for the selection of process technology.

Stack emission control equipment aspects

The advanced technologies in terms of emission controlling equipments (e.g. ESPs) can be used to control stack emissions of flue gases from coal power plants. Similar to the UK and the EU, in India ESPs and fabric filters are the recommended technologies (Soltanali et al., 2008) for removing particulates and heavy metals. In case of particulate control, filter bag house performs at 99 % efficiency continually, whereas performance of ESP declines over the years if not maintained regularly. Sengupta (2007) has observed that the rate at which design efficiency of ESP declines is 1 % per year. Also, the low sulphur content of coal turns down dust removal efficiency of ESP significantly. According to Wang et al. (2001), reduction in dust removal efficiency was found to be 2.47 % when sulphur content in coal was lowered from 1.25 to 0.65 %. Based on these results, the CPSE model takes into account either ESP or filter bag house as two alternatives for particulate control equipment along with installation, up-gradation year and design efficiency of ESP. The CPSE model also reflects the effect of low sulphur content in coal on ESP if it has been used in a coal power plant.

Generally, Low NO_x Burners (LNBs), selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR) are used for NO_x emission control as needed based on existing power plant technology (Chikkatur and Sagar, 2007). It has been observed that SCR system can reduce 70–90 % while SNCR system can remove 30–70 % of NO_x emissions from coal power plants. Accordingly, the CPSE model uses NO_x emission factor based on various control options as no control, LNB, SCR, SNCR, combined LNB and SCR as well as combined LNB and SNCR.

Significant reduction in SO_2 emissions was observed due to wide application of the flue gas desulphurization (FGD) technology in China (Zhao et al. 2008). Miller et al. (2006) stated that dry FGD systems can attain 90–95 % SO_2 emission control and are typically used at plants burning low-sulphur coal, whereas wet FGD systems can attain 95–98 % SO_2 emission control and are typically used at plants burning high-sulphur coal. Therefore, to incorporate SO_2 control mechanism three options are offered in CPSE model, which are (1) no control available, (2) dry FGD and (3) wet FGD.

It is worth noting that the control equipments used for particulate and SO_2 abatements also remove Hg emissions to a certain extent as a co-benefit. According to Tian et al. (2010), control equipments like ESP, FF and FGD are also responsible for the removal of Hg emissions by about 33, 68 and 57 %. These co-benefits are also taken into account in the CPSE model for estimating Hg stack emissions.

Table 1 Basic emission rate for CO_2 used in CPSE Model (kt/GWh)

Process technology	CCS	
	Yes	No
Sub-critical	127	913
Super-critical	109	830
Ultra-supercritical	94	738
IGCC	101	824

Basic emission rates

Unfortunately, there is no field study that gives CO_2 and NO_x emission factors for Indian coal power plants considering effects of important aspects like plant technology, process attributes and control equipments. However, Beer (2007) and Zhao et al. (2008) have provided emission rates of CO_2 and NO_x, respectively, based on these important aspects. Accordingly, in CPSE model, the estimation of CO_2 stack emissions is based on emission rates given by Beer (2007) for various process technologies used in coal power plants with and without CCS while the estimation of NO_x emissions is based on emission factors given by Zhao et al. (2008) according to boiler type and control equipments used. Table 1 and 2 give basic emission rates for CO_2 and NO_x used in the proposed CPSE model.

Results and discussion

In the present study, stack emissions have been estimated using the proposed CPSE model for Badarpur Thermal Power Station (BTPS), New Delhi, from 2000 to 2008. The user form of CPSE model giving the information about requirement of various input variables of a coal power plant is shown in Fig. 1.

The input data required for stack emission estimation were obtained from various publications like performance review reports published by Central Electricity Authority (CEA), CBIP (Central Board of Irrigation and Power) (1997) and TERI (The Energy and Resources Institute) (2011). The characteristics of BTPS, New Delhi, which were taken into consideration for stack emission estimation are listed in Table 3.

Particulate emissions

The particulate stack emissions and coal consumption in BTPS, New Delhi, during 2000–2008 are illustrated in Fig. 2a for TSP and PM_{10}, and in Fig. 2b for $PM_{2.5}$.

During 2000–2004, emissions of TSP, PM_{10} and $PM_{2.5}$ were initially high enough to reach to around 32, 25 and 1.6 kt, respectively. However, in 2004 due to the up-

Table 2 Basic emission rate for NO_x used in CPSE Model (t/kt)

Type of boiler	No control	Low NO_x burner	Selective catalytic reduction	Low NO_x burner and selective catalytic reduction	Non-selective catalytic reduction	Low NO_x burner and Non-selective catalytic reduction
Tangentially fired	6.6	4.05	1.32	0.81	3.3	2.03
Swirl burner	7.4	5.46	1.48	1.09	3.7	2.73

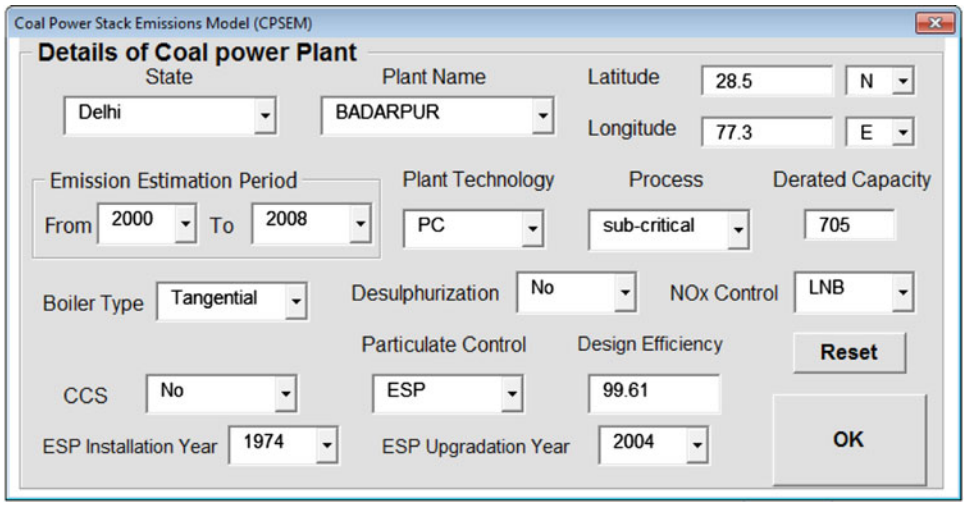

Fig. 1 User form of CPSE Model

Table 3 Characteristics of Badarpur Thermal Power Station, New Delhi (CBIP (Central Board of Irrigation and Power) 1997; TERI (The Energy and Resources Institute) 2011)

	Characteristics
Derated capacity (MW)	705
Plant technology	Pulverized coal
Type of boiler	Tangentially fired
Process technology	Sub-critical
Desulphurization	No
NO_x control technology	Low NO_x burner
Particulate control equipment	Electro static precipitator
Year of ESP Installation	1978
year of ESP up-gradation	2004
Design efficiency of ESP (%)	99.61

gradation of ESPs there was sudden decrease of about 90 % in all types of particulate emissions from stacks. Later on, particulate emissions in 2008 increased to about 2.5 times compared with those of 2005. It is observed that increasing trends of all types of particulate stack emissions from 2005 to 2008 were not similar or equivalent to trend of coal consumption. A possible reason for this could be the declining efficiency of electrostatic precipitator over the years (Sengupta, 2007).

Gaseous pollutants emissions

The emission of gaseous pollutants (SO_2, NO_x) and coal consumption in BTPS, New Delhi, during 2000–2008 are illustrated in Fig. 3. Stack emissions of both SO_2 and NO_x increased from 2000 to 2001 by 10 % and later on decreased by about 6 % between 2001 and 2003. Since then it increased gradually up to 2006, subsequent to the trend of coal consumption in power plant. There was sudden rise (12 %) in NO_x and SO_2 emissions in 2007 because of rapid increase in fuel consumption which gradually increased thereafter. An increase of about 24 % was observed in both SO_2 and NO_x emissions from 2003 to 2008 as no control measures for SO_2 emissions had been used during that period in the plant. As far as NO_x emission control is considered, LNB had been implemented in the plant. In spite of availability of LNB in the plant for NO_x control, the rapid growing trend of NO_x emissions during 2003 to 2008 implies that the emission control effect of LNB was quite poor and requires implementation of improved control policy. Also, it is very important to provide desulphurisation policy to combat sulphur emissions.

GHG and hazardous pollutant emissions

Figure 4a, b demonstrates GHG (CO_2) and hazardous pollutant (Hg) stack emissions along with electricity

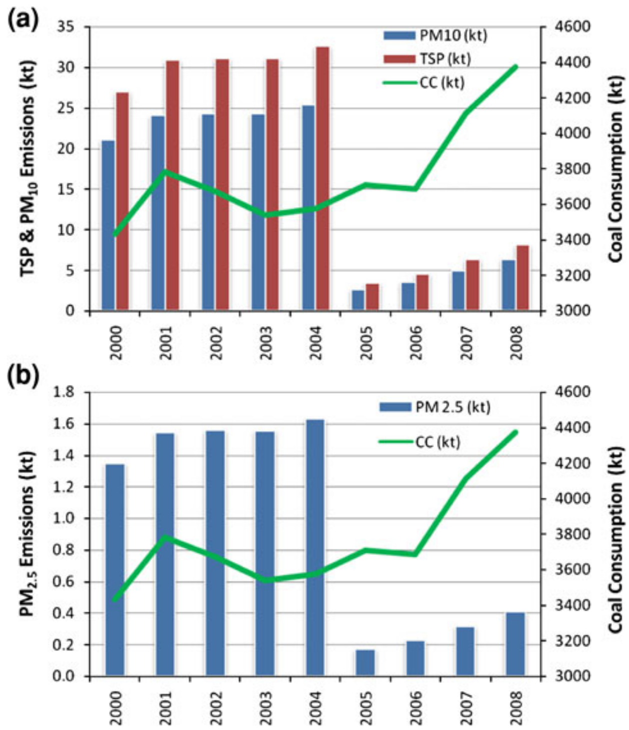

Fig. 2 Estimated Emissions of Particulates and coal consumption in BTPS, New Delhi during 2000–2008 **a** TSP, PM_{10} **b** $PM_{2.5}$

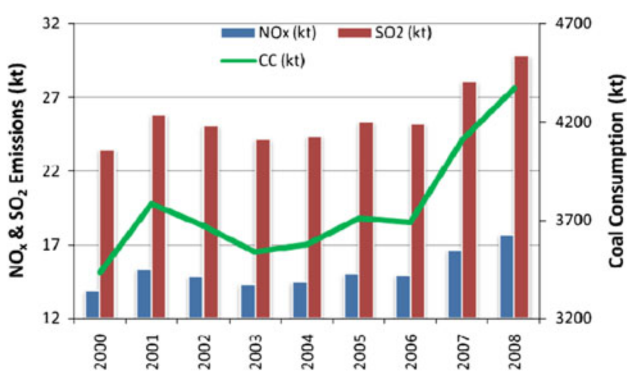

Fig. 3 Estimated gaseous pollutants emissions (SO_2, NO_x) and coal consumption in BTPS, New Delhi during 2000–2008

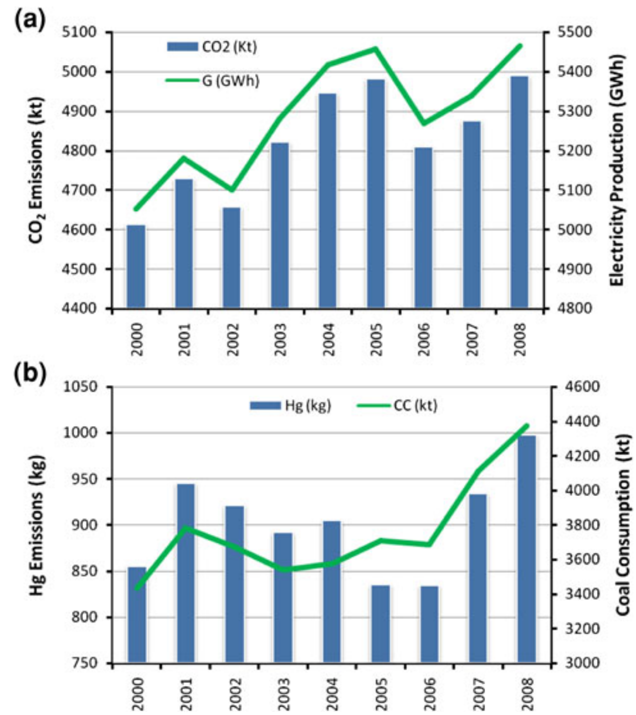

Fig. 4 Estimated GHG and Hazardous Pollutant Emissions from BTPS, New Delhi during 2000–2008 **a** CO_2 and electricity production **b** Hg and coal consumption

production and coal consumption from BTPS, New Delhi, from 2000 to 2008, respectively. The emission trend of CO_2 emissions was similar to electricity production of the plant, whereas Hg emission trend can be seen similar to that of gaseous pollutants following the trend of coal consumption. The reduction in GHG stack emissions was noticed in 2002 and 2006 relative to lowered electricity production in the plant, whereas Hg emissions decreased from 2001 to 2006. Thereafter, Hg emissions increased relative to coal consumption up to 2008. The overall increase in GHG stack emissions was from 4,600 kt in 2,000–5,000 kt in 2008. It is also noticed that Hg stack emissions were increased by 25 % during 2006–2008 even after up-gradation of ESP. A new effective control policy, therefore, should be planned to control hazardous mercury emissions and to avoid significant health impacts incurred therein.

With the application of correction factors discussed in "Materials and methods", the CPSE model revealed plant- and year-specific emission factors for BTPS, New Delhi, depending upon the plant characteristics as shown in Table 4.

Model evaluation/validation

The stack monitoring results are generally used to compare the emission performance of the plant with the current standards while the plant conditions are optimal (Vijay et al., 2004). Also, Lack of randomness in measurements and low measurement frequency gives rise to unfair annual stack emission estimations. Therefore, CPSE model has been validated by comparing trends of percentage change in annual emission estimations from the model with the observed ambient air concentrations of particulate matter (TSP and PM_{10}) and SO_2 during 2000–2008 at nearby air quality monitoring stations. There are two air quality monitoring stations nearby BTPS; Siri Fort and Nizamuddin. The air quality monitoring station at Siri Fort is comparatively nearer than that of Nizamuddin from BTPS,

Table 4 Emission factors revealed for BTPS New Delhi by CPSE model

Year	Emission factor for				
	NO_x (g/KWh)	SO_2 (g/KWh)	TSP (g/KWh)	CO_2 (g/kg)	Hg (g/t)
2000	2.75	4.64	5.34	1.34	0.249
2001	2.96	4.98	5.96	1.25	0.250
2002	2.92	4.91	6.10	1.27	0.251
2003	2.71	4.57	5.89	1.36	0.252
2004	2.67	4.50	6.01	1.38	0.253
2005	2.75	4.64	0.62	1.34	0.225
2006	2.84	4.78	0.86	1.30	0.226
2007	3.12	5.26	1.19	1.19	0.227
2008	3.24	5.46	1.49	1.14	0.228

New Delhi. The observed concentrations of TSP, PM_{10} and SO_2 at these two monitoring stations during 2000–2008 are adapted from online environmental data bank provided on website of Central Pollution Control Board (CPCB), New Delhi.

Total suspended particles (TSP)

Figure 5a, b illustrate the comparison of percentage change in annual TSP emissions and observed TSP concentrations at air quality monitoring stations namely Siri Fort and Nizamuddin.

Figure 5a, b illustrate that the trends of percentage rise and drop in annual emissions and observed concentrations of TSP are matching for all 8 years at Siri Fort while in 5 years at Nizamuddin monitoring station. The matching trends make it clear that ambient TSP concentrations are significantly influenced by emissions from BTPS, New Delhi. As Siri fort is the nearest monitoring station from BTPS than Nizamuddin, BTPS seems to significantly contribute and influence TSP concentrations at Siri Fort than Nizamuddin.

Respirable suspended particulate matter (PM_{10})

Figure 6a, b show the comparison of percentage change in annual PM_{10} emissions and observed PM_{10} concentrations at air quality monitoring stations namely Siri Fort and Nizamuddin.

This is observed that for PM_{10} the trends of percentage increase and decrease in annual emissions and observed concentrations are matching during almost all years except 2000–01 at relatively near monitoring station of Siri Fort, whereas the trends are similar for 6 years at Nizamuddin. This difference could be because of the differences in location of two air quality monitoring stations. The monitoring station at Nizamuddin is comparatively at a farther distance from BTPS and also local transport activities are the major source of PM_{10} concentrations (Nagpure, 2011).

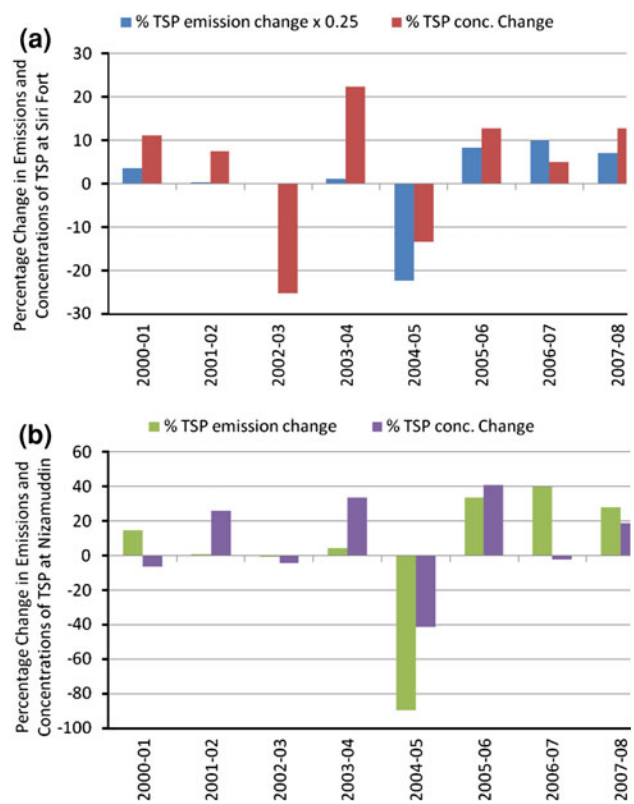

Fig. 5 Comparison of percentage change in annual TSP emissions and observed TSP concentrations at monitoring stations namely **a** Siri Fort **b** Nizamuddin

Sulphur dioxide (SO_2)

Figure 7a, b illustrate the comparison of percentage change in annual SO_2 emissions and observed SO_2 concentrations at air quality monitoring stations namely Siri Fort and Nizamuddin.

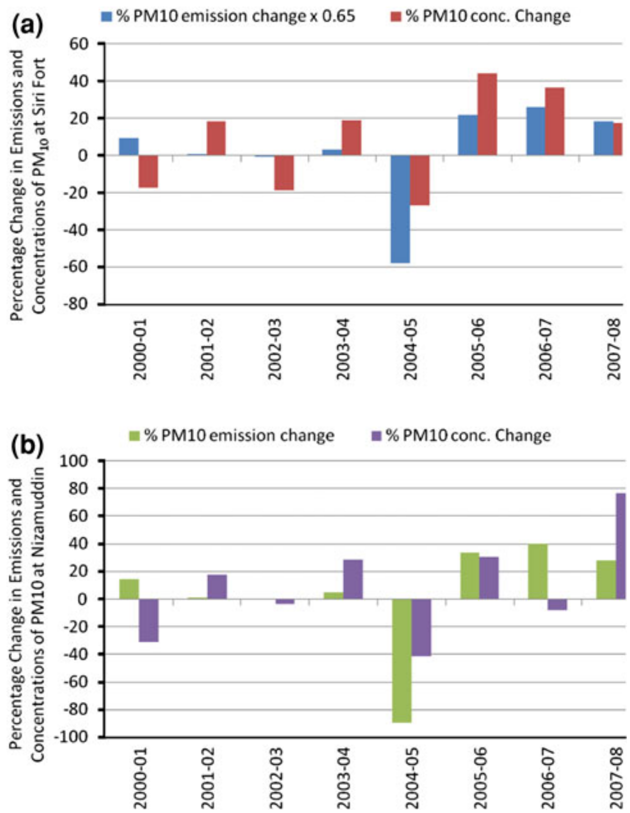

Fig. 6 Comparison of percentage change in annual PM_{10} emissions and observed PM_{10} concentrations at monitoring stations namely **a** Siri Fort **b** Nizamuddin

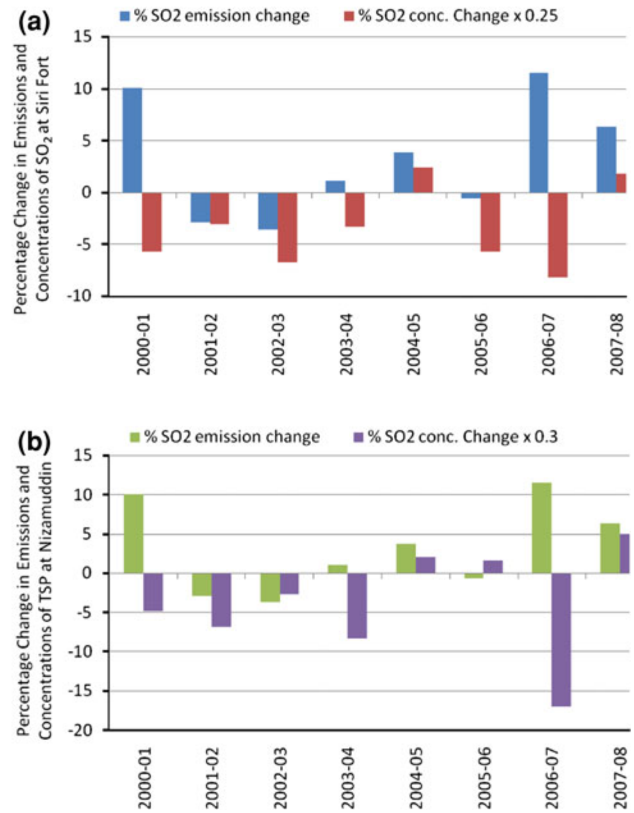

Fig. 7 Comparison of percentage change in annual SO_2 emissions and observed SO_2 concentrations at monitoring stations namely **a** Siri Fort **b** Nizamuddin

The trends of percentage change in annual emission estimates and observed concentrations of SO_2 are matching during 5 years (2001–2002, 2002–2003, 2004–2005, 2005–2006 and 2007–2008) at air quality monitoring station of Siri Fort whereas for 4 years (2001–2002, 2002–2003, 2004–2005 and 2007–2008) at Nizamuddin. It is quite obvious that nearby sources at both monitoring stations (especially transportation activities on ring road and Mathura road adjoining to Siri Fort station) can influence SO_2 concentrations proportionally. Diesel sulphur reduction program was implemented in 2000–2001 for all private and diesel vehicles in National Capital Territory (NCT) (CPCB, 2010). This resulted in dramatic decrease in ambient SO_2 concentrations during 2000–2001. The high volume of commercial vehicles from Faridabad enters into Delhi through Mathura road (DUDGD 2006) which is very near to Siri Fort air quality monitoring station. According to CPCB (2010), Haryana State government issued a notification in December 2003 according to that the age for the operation of various types of transport vehicles in Faridabad had been fixed. Accordingly, phasing out of age old commercial vehicles in Faridabad could lead in lowering SO_2 emissions during 2003–2004 at Siri Fort station. Delhi Government had also implemented mandatory Compressed Natural Gas (CNG) norms for light commercial vehicles (LCVs) in 2006 resulting into higher increase in CNG driven LCV population in 2007 to help reduce ambient SO_2 concentrations during 2006–2007. Thus, contribution of vehicular emissions of SO_2 could be a factor that might also influence the air quality concentration of SO_2 proportionally at monitoring stations.

The above-mentioned and discussed matching trends in stack emission estimations and ambient air quality concentrations of TSP, PM_{10} and SO_2 indicate that the proposed CPSE model works satisfactorily.

Conclusion

In the present study we have made an attempt to propose first ever plant-specific multi-year, multi-parameter stack emission model; namely Coal Power Stack Emission (CPSE) model, for Indian conditions. The CPSE model has been developed using MS Excel and Visual Basic Application (VBA). This model can be used to explore current and historical annual stack emissions from a coal based power plant taking into account essential variables. The CPSE model is applied to get historical and present emission trends from Badarpur Thermal Power Station (BTPS), New Delhi considering the essential variables like coal characteristics, process attributes, and control equipment features. The model results are successfully evaluated/validated by comparing the trends of percentage change in annual TSP, PM_{10} and SO_2 emissions and observed concentrations at nearby air quality monitoring stations namely Siri Fort and Nizamuddin. Study results indicate that the stack emission estimations from CPSE model reflect effects of different policy changes and technological interventions introduced in plant from time to time. Thus, we feel the proposed model can effectively be used to estimate stack emissions from coal based thermal power stations particularly in Indian conditions. We hope this will bridge the gap that presently exists in India in the area of stack emission estimation modelling for any coal based power plant. The results of stack emission estimations from CPSE model can further be useful for air quality assessment studies.

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