Quantifying Baseline Emission Factors of Air Pollutants in China's Regional Power Grids

ARTICLE *in* ENVIRONMENTAL SCIENCE & TECHNOLOGY · MARCH 2013

Impact Factor: 5.33 · DOI: 10.1021/es304915q · Source: PubMed

Wenjia Cai
Tsinghua University

Can Wang
Tsinghua University

Environmental Science & Technology

Policy Analysis

pubs.acs.org/est

Quantifying Baseline Emission Factors of Air Pollutants in China's Regional Power Grids

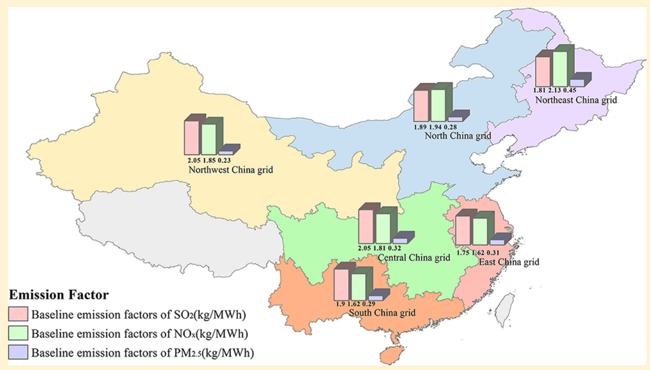
Wenjia Cai,[†,‡] Can Wang,*[,†,‡] Zhugang Jin,[†,‡] and Jining Chen[‡]

[†]Ministry of Education Key Laboratory for Earth System Modeling, and Center for Earth System Science, Tsinghua University, Beijing, China

[‡]State Key Joint Laboratory of Environment Simulation and Pollution Control (SKLESPC), and School of Environment, Tsinghua University, Beijing, China

S *Supporting Information*

ABSTRACT: Drawing lessons from the clean development mechanism (CDM), this paper developed a combined margin methodology to quantify baseline emission factors of air pollutants in China's regional power grids. The simple average of baseline emission factors of SO_2, NO_X, and $PM_{2.5}$ in China's six power grids in 2010 were respectively 1.91 kg/MWh, 1.83 kg/MWh and 0.32 kg/MWh. Several low-efficient mitigation technologies, such as low nitrogen oxide burner (LNB), were suggested to be replaced or used together with other technologies in order to virtually decrease the grid's emission factor. The synergies between GHG and air pollution mitigation in China's power sector was also notable. It is estimated that in 2010, that every 1% CO_2 reduction in China's power generation sector resulted in the respective coreduction of 1.1%, 0.5%, and 0.8% of SO_2, NO_X, and $PM_{2.5}$. Wind is the best technology to achieve the largest amount of coabatement in most parts of China. This methodology is recommended to be used in making comprehensive air pollution control strategies and in cobenefits analysis in future CDM approval processes.



1. INTRODUCTION

Power generation is one of the largest contributors to a country's emissions, either in terms of greenhouse gas (GHG) or conventional air pollutants. Therefore, there is an urgent need to develop scientific and comprehensive GHG and conventional air pollutants mitigation plans in this sector, especially in developing countries who are the primary contributors to global emissions growth.

To achieve this goal, people usually evaluate and compare each measure's effectiveness in reducing emissions. A reference is needed to achieve the evaluation of emission reduction. In the domain of GHG mitigation, people use grid-based CO_2 baseline emission factors as the references and they have been widely used in clean development mechanism (CDM).[1] A proposed CDM project activity (such as connecting a new solar PV plant into a grid) is believed to influence the way that electricity is generated within that grid system in two aspects. First, it will affect the electricity generation of a group of existing power plants. Second, it will affect the construction and future operation of a group of prospective power plants. Each of the two groups of power plants being affected has an emission factor, named as the "operating margin" (OM) and the "build margin" (BM) respectively. The weighted average of OM and BM—termed the "combined margin" (CM)—is then taken as the CO_2 baseline emission factors for this specific proposed CDM project activity. In the field of conventional air pollutants abatement, we witness a divergence of methodologies in data-rich and data-poor regions. In California, England, and the U.S.,[2−4] researchers are able to use dispatch models and regressions of hourly historical data to estimate the marginal emission factors, which reflect the emissions intensities of the marginal generator in the system. In regions where there is a lack of data, researchers usually take one common-practice technology as the reference, and then measure other technologies' effects in reducing emissions. Obviously, the methodologies to measure CO_2 reduction effects and conventional air pollutants reduction effects are different, which is not good for making comprehensive mitigation strategies. Innovatively, the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model developed by International Institute for Applied Systems Analysis (IIASA) and other cooperating agencies[5] has uniformly used the combined margin approach in CDM to calculate the GHG and conventional air pollutants emissions factors for grid electricity in 2005. The GAINS results have been cited in Rive and Aunan's study[6] in quantifying the air quality cobenefits of CDM projects in China. However, as

Received: December 1, 2012
Revised: March 4, 2013
Accepted: March 5, 2013
Published: March 5, 2013

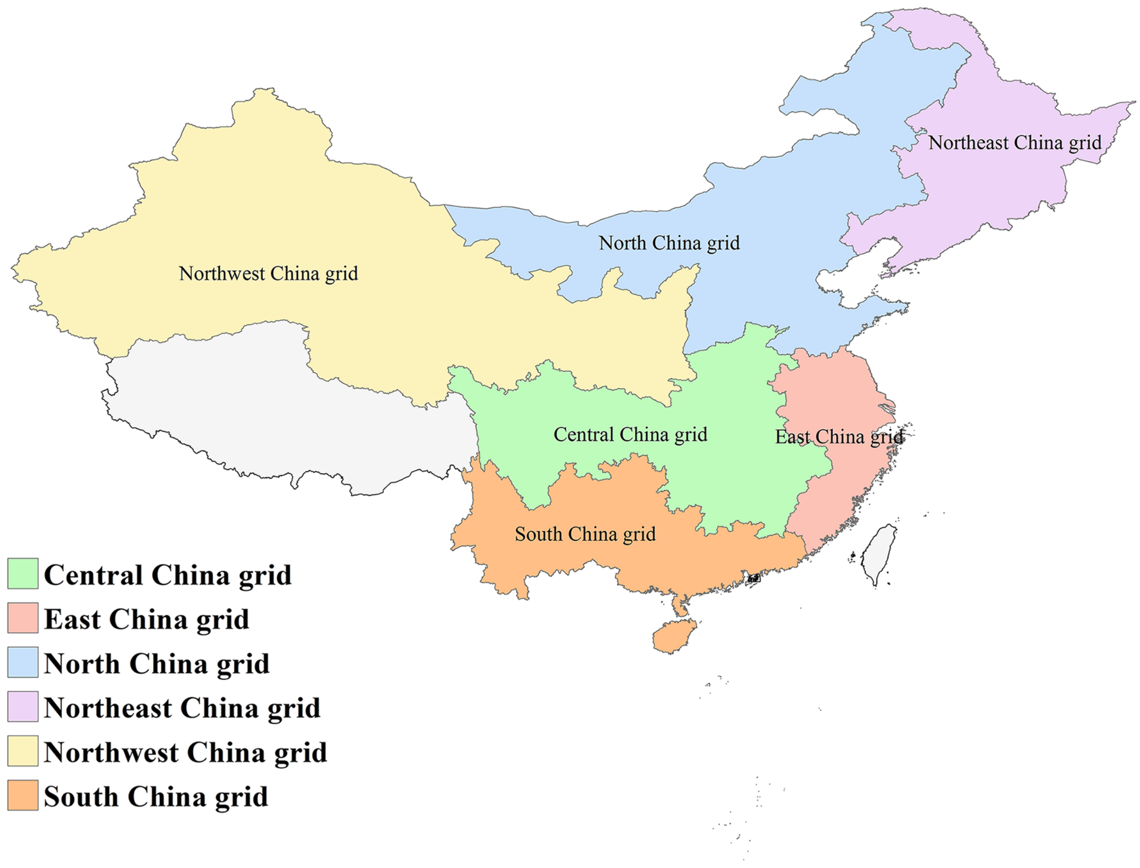


Figure 1. Geographical location of six power grids in China.

GAINS is a scenario-based optimization tool to identify the least-cost comprehensive emission control strategies, and the current starting year of scenarios is 2005, it constrains its ability to give a latest update on baseline emission factors of the grids and brings forth the demand to develop a universal tool for timely evaluation of baseline emission factors.

In this paper, we take China's power generation sector as a case, and develop the methodology to quantify grid-based emission factors of air pollutants based on lessons drawn from CDM. The location of China's six power grids is displayed in Figure 1. Rather than taking only one technology for reference, this approach takes each grid's diverse generation structures and in-use mitigation measures into consideration. Thus, it provides a more scientific and objective view for evaluating the abatement effects of different power generation technologies. More importantly, due to the unified methodologies, it can be used to evaluate the GHG and air pollution interactions and synergies, which can facilitate making a more comprehensive and effective mitigation strategy.

In Section 2, we introduce the method of calculating grid-based emission factors of air pollutants. In Section 3, we elaborate upon the data sources and main assumptions for the calculation. We then show in Section 4 the results of grid-based emission factors and the findings about the most sensitive parameters. Finally, we discuss the implications of the grid-based baseline emission factors in two aspects and make comments on the methodology in Section 5.

2. METHOD OF QUANTIFYING BASELINE EMISSION FACTORS OF AIR POLLUTANTS IN CHINA'S REGIONAL POWER GRIDS

In this study, we define air pollutants in power grids as SO_2, NO_X, and $PM_{2.5}$. Similar to the CDM project, quantifying the OM and BM of SO_2, NO_X, and $PM_{2.5}$ in each grid is the precondition to quantify baseline emission factors.

2.1. Methodology to Calculate OM of SO_2, NO_X, and $PM_{2.5}$. As mentioned in the Introduction section, the OM (the operating margin) is the emission factor that refers to the group of existing power plants whose current electricity generation would be affected by the technology. In CDM, people can choose from several different ways to calculate the OM.[1] The main differences among these different ways are the energy mix and the operation pattern of the power grid, as well as the data availability. According to China's national circumstance and data availability statuses, China is suitable to use the "simple OM" method. Similarly, in this study, we also use this simple OM method to calculate the OM of SO_2, NO_X, and $PM_{2.5}$. The simple OM ($EF_{OM,g,p,y}$) of pollutant p in grid g is calculated as the generation-weighted average emissions of air pollutants per electricity unit ($t SO_2$/MWh, $t NO_X$/MWh, $t PM_{2.5}$/MWh) of all generating sources serving the system for the most recent 3 years (y, $y - 1$, $y - 2$) when data is available, not including low-cost/must-run power plants. It should be noted that low-cost/must run resources are defined as power plants with low marginal generation costs or dispatched independently of the daily or seasonal load of the grid. They include hydro, geothermal, wind, low-cost biomass, nuclear and solar generation. If a fossil fuel plant is dispatched independently of the daily or seasonal load of the grid and if this can be demonstrated based on the publicly available data, it should be considered as a low-cost/must-run.[1] However, as China does not have publicly available dispatch data, all fossil fuel plants are not low-cost/must-run power plants.

$$EF_{OM,g,p,y} = \frac{\sum_i Q_{g,i,p,y} + \sum_i Q_{g,i,p,y-1} + \sum_i Q_{g,i,p,y-2}}{GEN_{g,y} + GEN_{g,y-1} + GEN_{g,y-2}} \quad (1)$$

where $Q_{g,i,p,y}$ is the amount of emissions of air pollutant p (ton) from fuel i (in a mass or volume unit) in year y in grid g; $GEN_{g,y}$ is the electricity (MWh) delivered to the grid g, not including low-cost/must-run power plants. In fact, in China, power plants other than low-cost/must-run power plants are fossil-fueled power plants. Therefore, $GEN_{g,y}$ is actually the electricity produced by fossil-fueled power plants.

There are six power grids in China. As the Chinese statistics systems record/report the amount of emissions of air pollutants by province, it is needed to sum up the emissions in provinces which belong to grid g to get the grid-level emissions. Therefore, we have

$$Q_{g,i,p,y} = \sum_{j \in g} Q_{j,i,p,y} \quad (2)$$

where $Q_{j,i,p,y}$ is the amount of emissions of air pollutant p (ton) from fuel i in year y in province j which belongs to grid g.

$$\begin{aligned} Q_{j,i,p,y} = {} & F_{i,j,y} \times COEF_{i,j,p} \times \sum_n [(1 - \gamma_{p,n,y}) \times s_{p,n,j,y} \\ & \times \alpha_{p,n,j,y}] + \sum_n [s_{p,n,j,y} \times (1 - \alpha_{p,n,j,y})] \\ & + (1 - \sum_n s_{p,n,j,y}) \end{aligned} \quad (3)$$

where $F_{i,j,y}$ is the amount of fuel i consumed by province j in year y; $COEF_{i,j,p}$ is emission coefficient of pollutant p of fuel i in province j, under no control; $\gamma_{p,n,y}$ is the average removal efficiency of air pollutant p by pollutant removal equipment n in year y; $s_{p,n,j,y}$ is the share of production capacity installed with pollutant p removal equipment n in the total production capacity in province j in year y; $\alpha_{p,n,j,y}$ is the operation rate of pollutant p removal equipment n in province j in year y. Please refer to Table S1 in the Supporting Information (SI) for the detailed numbering of different technologies.

The value of $COEF_{i,j,NO_x}$ can be cited directly from the literature.[7] The values of $COEF_{i,j,SO_2}$ and $COEF_{i,j,PM_{2.5}}$ can be calculated based on the following equations:

$$COEF_{i,j,SO_2} = SC_{i,j} \times CR_{i,j} \times \frac{64}{32} \quad (4)$$

$$\begin{aligned} COEF_{i,j,PM_{2.5}} & = AC_{i,j} \times (1 - BA_{i,j}) \times \theta_{PM_{2.5i,j}} \text{ or} \\ & = COEF_{i,j,TSP} \times \theta_{PM_{2.5},i,j} \end{aligned} \quad (5)$$

where $SC_{i,j}$ is the sulfur content of fuel i in province j; $CR_{i,j}$ is the conversion rate of sulfur of fuel i in province j; $AC_{i,j}$ is the ash content of fuel i in province j; $BA_{i,j}$ is the percentage of bottom ash after burning fuel i in province j; $\theta_{PM_{2.5i,j}}$ is the ratio of $PM_{2.5}$ in the flue gas from fuel i in province j; $COEF_{i,j,TSP}$ is the emission coefficient of total suspended particles (TSP) from burning fuel i in province j.

In the case that a grid has net electricity imports from a connected electricity system within the same country, eq 1 should have minor transformations. The denominator (sum of each year's generation) should be added with the amount of net electricity imports in year y, $y - 1$ and $y - 2$. The numerator should be added with the emissions from those imported electricity. The average emission rate of the exporting grid is used to determine the emission factor for net imported electricity.[1]

2.2. Methodology to Calculate BM Emission Factors of SO_2, NO_X, and $PM_{2.5}$. The BM (build margin) is the emission factor that refers to the group of prospective power plants whose construction and future operation would be affected by the technology. Similar to CDM, the BM of air pollutants can also be calculated in several ways according to the availability of data. The most accurate one is to calculate the generation-weighted average emission factor of a sample of power plants m, noting that the sample group m should consist of either the five power plants that have been built most recently, or the power plant capacity additions in the electricity system that comprise 20% of the system generation and that have been built most recently. An alternative but more conservative way is to use the technology share of installed capacity that have been built most recently as the weight index, and combine this with the emission factor of the corresponding but most advanced commercialized technology (with pollutant removal equipment) to date in order to calculate the BM. However, in China's case, the current official statistics only report the summed installed capacity for all thermal-fired power plants and do not have the separate installed capacity data for different technologies (such as coal-fired, oil-fired, and gas-fired).[8] In order to understand the share of each technology, therefore, with reference to China's CDM practice, we must calculate the build margin emission factor of air pollutants. Here we use the energy balance table of the most recent available year to calculate the share of pollutant emissions in total emissions from coal-fired, oil-fired and gas-fired power generation ($\lambda_{i,p,gy,y}$), respectively. This share is used to represent the share of each technology. The detailed steps and equations are as follows:

Step 1: Calculate the share of SO_2, NO_X, and $PM_{2.5}$ emissions in total emissions respectively from coal-fired, oil-fired and gas-fired power generation in grid g;

$$\lambda_{i,p,g,y} = \frac{\sum_{j \in g} F_{i,j,y} \times EF_{p,i,j,y}}{\sum_{j \in g} F_{i,j,y} \times EF_{p,i,j,y}} (i = \text{coal, oil, gas}) \quad (6)$$

where $F_{i,j,y}$ is the amount of fuel i consumed by province j in year y; $EF_{p,i,j,y}$ is emission factor of pollutant p from fuel i in province j in year y, considering the installment of possible pollutant removal equipment; y is the latest year for which data is available.

Step 2: Calculate the corresponding emission coefficient of pollutant p of thermal-fired power generation technology

$$\begin{aligned} EF_{thermal,p,g,y} = {} & \lambda_{coal,p,g,y} \times EF_{coal,adv,p,g,y} \\ & + \lambda_{oil,p,g,y} \times EF_{oil,adv,p,g,y} \\ & + \lambda_{gas,p,g,y} \times EF_{gas,adv,p,g,y} \end{aligned} \quad (7)$$

where $EF_{coal,adv,p,y}$, $EF_{oil,adv,p,y}$, and $EF_{gas,adv,p,y}$ are respectively the emission factors of pollutant p of the most advanced commercialized coal-fired, oil-fired, and gas-fired power

Table 1. Baseline Emission factors of SO_2 in China's Regional Power Grids

grid	OM (kg/MWh) 2008	OM 2009	OM 2010	OM the weighted average of three-year OM	BM (kg/MWh) 2010	CM (kg/MWh) wind and solar PV	CM others	annual average change rate of CM	assuming the highest grid CM equals 100
north	4.47	3.63	2.51	3.47	0.31	**2.68**	**1.89**	−25%	92.2
northeast	4.91	3.27	2.33	3.46	0.16	**2.64**	**1.81**	−31%	88.3
east	3.76	3.29	2.51	3.15	0.35	**2.45**	**1.75**	−18%	85.2
central	5.29	4.00	2.68	3.88	0.23	**2.96**	**2.05**	−29%	100.0
northwest	6.25	3.41	2.28	3.82	0.28	**2.94**	**2.05**	−39%	99.9
south	4.95	3.58	2.70	3.66	0.14	**2.78**	**1.90**	−26%	92.5
national average							**1.91**	−28%	

generation technologies, considering the installment of possible pollutant removal equipment. Taking $EF_{coal,adv,p,g,y}$ for example:

$$EF_{coal,adv,p,g,y} = \frac{3600 \times \frac{COEF_{coal,p,g,y}}{NCV_{coal,y}} \times [(1-\gamma_{adv,p,y}) \times s_{adv,p,y} + (1-s_{adv,p,y})]}{\eta_{coal}} \quad (8)$$

where $COEF_{coal,p,g,y}$ is the no-control emission coefficient of pollutant p of coal in grid g in year y (unit: t/t, t/km^3); $NCV_{coal,y}$ is the net heat value of coal in year y (for coal and oil, the unit is MJ/t; for gas, the unit is MJ/km^3); $\gamma_{adv,p,y}$ is the average removal rate of pollutant p in year y of the most advanced commercialized pollution control technology; $s_{adv,p,y}$ is the share of the most advanced commercialized pollution control technology targeting at pollutant p installed in new built coal-fired plant in year y; η_{coal} is the generation efficiency of the most advanced commercialized coal-fired generation unit.

Step 3: Calculate the build margin of the grid g

$$EF_{BM,p,g,y} = \frac{CAP_{thermal,g,y}}{CAP_{total,g,y}} \times EF_{thermal,p,g,y} \quad (9)$$

where $CAP_{total,g,y}$ is the total power plant capacity additions in grid g that comprises just more than 20% of the grid generation and that have been built most recently; $CAP_{thermal,g,y}$ is the thermal power plant capacity additions, which is included in $CAP_{total,g,y}$.

2.3. Methodology to Calculate CM Emission Factors of SO_2, NO_X, and $PM_{2.5}$. As mentioned above, the baseline emission factors of SO_2, NO_X, and $PM_{2.5}$ (i.e., $EF_{CM,p,g,y}$) are the weighted average of corresponding OM and BM. The essence of weighting OM and BM is to describe "what part of electric power will be affected by this new CDM project". As described in the introduction session, a new CDM project in the power sector is going to affect some amount of electricity generated by the existing power plants, and meanwhile affect some new power plants from entering the grid. If a new CDM project is more likely to replace the electricity generated by the grid, rather than the addition of new power plants, the weight of OM for this project should be bigger than that of BM. And Vice versa.

For wind and solar power generation projects, the CDM Executive Board (EB) suggests using default weighting factors of 0.75 and 0.25.[1] As these projects have intermittent and nondispatchable nature, they may have limited capacity value. Besides, a wind/solar project's capacity value is usually lower than that of a typical grid resource. Therefore, it is believed that these projects will in more cases affect the electricity generated by the existing power plants, rather than the entry of new power plants. That is why the OM weight for wind and solar projects is bigger than the BM one. For other renewable CDM projects, the CDM EB suggests using default weighting factors of 0.5 and 0.5.

In this study of quantifying different technologies' baseline emission factors of air pollutants, we follow the weight settings for CDM.

3. DATA SOURCES AND MAIN ASSUMPTIONS

Our estimates of OM, BM are based on the historic emissions and generation data. OM, BM of SO_2, NO_X, and PM for six electric grids in China have been estimated in this paper. The grids are respectively North, Northeast, East, Central, Northwest, and South grid. The detailed provinces and municipalities covered by each grid can be found in section II of the SI.

$GEN_{g,j}$ is calculated based on China Electricity Yearbooks (2007−2011).[9] For net electricity imports from a connected electricity system, they are cited from the Electric Power Industry Statistical Information Compilation (2008−2010).[10] $F_{i,j,y}$ is cited from the China Energy Statistical Yearbook (2009−2011). $COEF_{i,j,p}$ is calculated based on literature and research reports (i.e., refs 7, 11−15). $\gamma_{p,n,y}$ is mainly based on ref 7. The $s_{SO_2,n,j,y}$ in 2008−2010 are calculated based on the complete list of desulphurization facilities in coal-fired units in China.[16] As there are dozens of desulphurization technologies in operation, several technologies are selected to calculate their detailed value of $s_{SO_2,n,j,y}$based on the following two criteria: first, they have the biggest shares in total installations; second, their summed-up shares reach over 90%. The $S_{NO_x,n,j,y}$ in 2010 are calculated based on the complete list of denitrification facilities in coal-fired units in China.[17] And the $S_{NO_x,n,j,y}$ in 2008 and 2009 are estimated respectively from literature[18] and the China Electricity Yearbook 2011. There is no list for dust removal equipment at the national or provincial level. Therefore we assume the share of dust removal equipment installation in each province equals the national value. As the share value in 2005 and 2010 which is, respectively, 94% and 95%, for conservative purposes, we assume the shares from 2008 to 2010 are all equal to 95%. The detailed shares and assumptions for each type of dust removal equipment $s_{PM_{2.5},n,j,y}$ can be found in section IV in the SI. The value of $\alpha_{SO_2,n,j,y}$ is estimated based on the goal for the end of 11th five-year period, together with the actual amount of SO_2 emitted in 2008,[19] and is assumed to be remained at 95% from 2008 to 2010. Due to the lack of data and for conservative purposes, the $\alpha_{p,n,j,y}$ for NO_X and $PM_{2.5}$ are both assumed to be 100% from 2008 to 2010. The estimations of $EF_{coal,adv,p,y}$, $EF_{oil,adv,p,y}$, and $EF_{gas,adv,p,y}$ rely on the pollutant

Table 2. Baseline Emission Factors of NO_X in China's Regional Power Grids

	OM (kg/MWh)				BM (kg/MWh)	CM (kg/MWh)			
grid	2008	2009	2010	The weighted average of three-year OM	2010	Wind and Solar PV	Others	annual average change rate of CM	assuming the highest grid CM equals 100
north	3.76	3.49	3.50	3.58	0.30	**2.76**	**1.94**	−4%	91.1
northeast	4.20	3.91	3.78	3.96	0.29	**3.04**	**2.13**	−5%	100.0
east	3.08	2.86	2.45	2.91	0.33	**2.27**	**1.62**	−11%	76.3
central	3.78	3.34	3.24	3.43	0.18	**2.62**	**1.81**	−7%	85.0
northwest	3.54	3.49	3.31	3.43	0.27	**2.64**	**1.85**	−3%	87.1
south	3.30	3.10	2.98	3.12	0.12	**2.37**	**1.62**	−5%	76.1
national average							**1.83**	−6%	

Table 3. Baseline Emission Factors of $PM_{2.5}$ in China's Regional Power Grids

	OM (kg/MWh)				BM (kg/MWh)	CM (kg/MWh)			
grid	2008	2009	2010	the weighted average of three-year OM	2010	Wind and Solar PV	Others	annual average change rate of CM	assuming the highest grid CM equals 100
north	0.53	0.48	0.45	0.48	0.10	**0.39**	**0.29**	−8%	63.7
northeast	0.88	0.77	0.71	0.79	0.12	**0.62**	**0.45**	−10%	100.0
east	0.54	0.50	0.47	0.50	0.14	**0.41**	**0.32**	−7%	70.2
central	0.66	0.56	0.53	0.58	0.07	**0.45**	**0.33**	−11%	71.8
northwest	0.44	0.39	0.35	0.39	0.07	**0.31**	**0.23**	−10%	50.7
south	0.62	0.53	0.49	0.54	0.05	**0.42**	**0.30**	−11%	65.3
national average							**0.32**	−9%	

removal information in the OM calculation and also used the parameter settings in China's CDM BM calculations, such as fuels' net calorific values and the generation efficiencies of the most advanced generating units.[8] Finally, the $CAP_{total,g,y}$ and $CAP_{thermal,g,y}$ are cited from the China Electricity Yearbooks from 2007 to 2011.

Please refer to section IV and V in the SI for further details.

4. RESULTS

Based on the method and data described above, the quantified baseline emission factors of air pollutants in China's regional power grids are displayed in Table 1, 2, and 3.

The national simple average baseline emission factors of SO_2, NO_X, and $PM_{2.5}$ in China's regional grids in 2010 were respectively 1.91 kg/MWh, 1.83 kg/MWh, and 0.32 kg/MWh for all technologies except wind and solar PV.

As OM stands for the average amount of pollutant emitted for every unit of power generation in the grid, we can find out the absolute value of emission intensity of SO_2, NO_X, and $PM_{2.5}$ in different grids in China from 2008 to 2010. For example, the emission intensity of SO_2 in different grids in China in 2010 fell within the range of 2.28−2.70 kg/MWh. It is also observed that the emission intensity of SO_2, NO_X, and $PM_{2.5}$ in China from 2008 to 2010 has declined respectively by 28%, 6%, and 9% each year. In fact, the OM value for SO_2 in this study is comparable to the official statistics. In 2008 and 2010, the SO_2 emissions from China's power sector were, respectively, 10.60 Mt and 9.56 Mt;[20] the electricity generated in China was, respectively, 3433 TWh and 4228 TWh.[9] Therefore, the SO_2 emission intensity in 2010 in China's power sector was 2.26 kg/MWh. The change of SO_2 emission intensity from 2008 to 2010 was −26.7%. These mean that both the absolute value and the change rate of SO_2 emission intensity in this study are comparable to the official data, which testifies the accuracy of this methodology and the confidence of this study. Although there are still some differences between our results and the observed data, those differences could be attributed to the divergence between our assumptions and the actual data which is unfortunately not available right now. For NO_X and $PM_{2.5}$, as the official data is not available, we are not able to carry out the similar comparison work here.

Results also show that the differences in baseline emission factors among grids can be as large as fifty percent. The central grid possesses the highest baseline emission factor of SO_2, followed by the northwest, south, north, northeast, and finally east grid. The difference of baseline emission factors between the central grid and the east grid is 14.8%. In the baseline emission factor of NO_X, the northeast grid has the highest value, followed by the north, northwest, central, east, and finally south grid. The difference between the northeast and the south grid is 23.9%. The northeast grid also has the highest baseline emission factor of $PM_{2.5}$, followed by the central, east, south, north, and last northwest. The different between the northeast and northwest is as high as 49.3%. On one hand, the differences in baseline emission factors represent the disparities in the energy mix and deployment level of pollutant control technologies in grids. The shares of nonthermal power units in the total installed capacity in 2010 in north, northeast, east, central, northwest and south China were quite different. The detailed shares were, respectively, 10%, 19%, 16%, 44%, 30%, and 44%.[9] The deployment levels of pollutant control technologies also vary a lot among grids. For example, the ratios of power units installed with SO_2 removal equipment in north and northwest China were, respectively, 81% and 62%. If other factors were the same among regions, those regions with higher percentage of nonthermal power units or higher installation rate of pollutant removal equipment are inclined to have smaller baseline emission factors of conventional air pollutants. On the other hand, the differences in baseline emission factors highlight the necessity of making pollution control strategies down to the grid scale. A unified national-scale SO_2 control strategies might be good for central China

Table 4. Comparison of technologies' emission reduction effects when using different references

technologies in air pollutants control		emission reduction effects compared to the grid's emission intensity with no pollutant control technologies (kg/MWh)						emission reduction effects compared to the grid's baseline emission factors (kg/MWh)					
		north	north - east	east	central	north - west	south	north	north - east	east	central	north - west	south
SO_2	wet limestone-gypsum FGD	9.67	5.98	7.84	11.40	9.81	10.39	1.38	1.50	1.34	1.45	1.53	1.35
	circulating fluidized bed FGD	9.16	5.66	7.43	10.80	9.30	9.84	0.88	1.18	0.92	0.85	1.02	0.81
	seawater FGD	9.16	5.66	7.43	10.80	9.30	9.84	0.88	1.18	0.92	0.85	1.02	0.81
	wet FGD by carbide slag-gypsum	9.67	5.98	7.84	11.40	9.81	10.39	1.38	1.50	1.34	1.45	1.53	1.35
	ammonia process	9.67	5.98	7.84	11.40	9.81	10.39	1.38	1.50	1.34	1.45	1.53	1.35
	dual alkali process	9.16	5.66	7.43	10.80	9.30	9.84	0.88	1.18	0.92	0.85	1.02	0.81
	semidry process	9.16	5.66	7.43	10.80	9.30	9.84	0.88	1.18	0.92	0.85	1.02	0.81
	magnesium oxide FGD	9.16	5.66	7.43	10.80	9.30	9.84	0.88	1.18	0.92	0.85	1.02	0.81
NO_X	LNB+SCR	4.82	5.38	3.84	4.65	4.59	4.25	1.40	1.53	1.19	1.29	1.34	1.14
	LNB Only	1.61	1.79	1.28	1.55	1.53	1.42	−1.81	−2.06	−1.37	−1.81	−1.72	−1.69
	LNB+SNCR	2.14	2.39	1.71	2.07	2.04	1.89	−1.28	−1.46	−0.94	−1.29	−1.21	−1.22
	LNB+SNCR+SCR	4.55	5.08	3.63	4.39	4.34	4.02	1.13	1.23	0.98	1.03	1.09	0.91
$PM_{2.5}$	electrostatic Precipitator (ESP) + Wet FGD	5.09	7.56	5.22	6.16	4.09	6.09	0.13	0.22	0.16	0.14	0.10	0.11
	ESP Only	4.88	7.24	5.00	5.91	3.92	5.84	−0.08	−0.09	−0.06	−0.12	−0.07	−0.14

whose SO_2 baseline emission factor is the highest among all grids, however, for northeast China, the more urgent control target should be the $PM_{2.5}$. The disparities in the baseline emission factors will also greatly influence a technology's emission reduction effects when it is used in different grids. We will further elaborate this in Section 5.

To analyze the extent of uncertainty from our assumptions to the results of baseline emission factors (i.e., the CM values), we have carried out a sensitivity analysis. We found that the CM of SO_2, NO_X, and $PM_{2.5}$ in the six power grids in China are generally sensitive to the operation rate of pollutant removal equipment and the average removal efficiency of the most important technologies. The detailed analysis processes as well as the value of the parameters could be found in the SI.

5. DISCUSSION

As mentioned in the Introduction, the grid-based baseline emission factors of air pollutants can provide a more scientific way to evaluate technologies' pollutant abatement effects. Moreover, they can facilitate the creations of a comprehensive air pollutant mitigation strategy through evaluating the GHG and air pollution synergies. We now explain them in detail and make comments on the methodology at the end.

5.1. Using Baseline Emission Factors to Evaluate Technologies' Pollutant Abatement Effects. To evaluate a technology's pollutant abatement effects, a reference value is needed. Table 4 shows the comparison of technologies' emission reduction effects when using (1) the grid's average emission intensity with no pollutant control technologies and (2) the grid's baseline emission factors as the reference value. As shown in the table, there are very significant differences between using power units with no emission control equipment and using baseline emission factors to evaluate technologies' pollutant abatement effects. Technologies' abatement effects can shrink by 90% or even 100%+ when using the latter one as a reference value.

It is not difficult to understand the shrinking. One technology's pollutant abatement effect equals the reference value subtracted by its own emissions. If the reference changes from "the emission coefficient of facilities with no emission control technologies" into "the baseline emission factors that already take facilities with pollutant control technologies into consideration", the baseline emission factors will inevitably become smaller, which leads to a smaller evaluation of the technologies' pollutant abatement effects.

It is also interesting to find that, after using baseline emission factors as the reference value, some technologies' pollutant abatement effects have become negative, as shown in red figures in Table 4. These technologies are LNB only and LNB +SNCR technologies used in NO_X reduction, and the ESP only technology in $PM_{2.5}$ reduction. This means that the emission intensity of facilities using only these technologies has fallen behind the value of the baseline emission factors. Using only these technologies will pull down the emission intensity of the whole grid. In order to further decrease the emission intensity of a grid, we have to use other abatement technologies simultaneously or replace them with more efficient technologies. These observations cannot be made if the grid's average emission intensity with no pollutant control technologies is used as the reference. From this perspective, the baseline emission factors do provide a more scientific view for evaluating the abatement effects of different power generation technologies and can support a more scientific and effective way of designing pollutant control strategies.

5.2. Pollutant Coabatement Rates of CO_2 Mitigation Measures in China's Power Grids. This study unifies the methodologies of quantifying baseline emission factors of air pollutants and of CO_2 in China's power grids, which makes it easier to explore the cobenefits of CO_2 mitigation in air pollutants reduction. This will also greatly facilitate the formation of comprehensive pollutant control strategies.

dx.doi.org/10.1021/es304915q | Environ. Sci. Technol. 2013, 47, 3590−3597

To quantify the air pollutants coabatement rates of CO_2 mitigation measures in China's power grids, we use the CDM projects in China's power generation sector to represent the CO_2 mitigation measure. Until December 31st 2011, there were a total of 1530 CDM projects approved by the CDM Executive Board (EB), as shown in Table 5. As the "other" type (mainly district heating and higher efficiency coal power plant) only made up 0.5% and 2% in total project numbers and total emission reduction, respectively. To focus our study and to make the calculation less ambiguous, we ignore this type and concentrate on other types of CDM projects: hydro, wind, biomass, solar PV, and fuel switch (from coal to gas).

Table 5. China's Approved CDM Projects in Power Generation Sector until the End of 2011

type of CDM project	no. of projects	total amount of emission reductions each year ($ktCO_2e$/yr)	power generated each year (GWh/yr)
hydro	806	97 139	114 374
wind	611	79 355	80 640
biomass	58	8340	8130
solar pv	22	887	672
fuel switch	25	25 433	72 860
others	8	4365	na
total	1530	215 518	276 676

The CO_2 reduction effects of those CDM projects can be accessed from their project design documents (PDDs). Different CDM projects' air pollutants reduction effects should be calculated differently according to their emission characteristics. For zero-emission CDM projects (hydro, wind and solar PV), their air pollutants reduction effects equal the amount of power generated (accessible from PDDs) multiplied by the corresponding air pollutants baseline emission factors. For nonzero-emission CDM projects (biomass and fuel switch), their air pollutants reduction effects are the results of subtraction between the product of power generation and baseline emission factors and the emissions made by themselves. In calculating CDM projects' conventional pollutants' emissions, we assume that they have all installed the most advanced emission reduction technologies available in the grid.

Table 6 displays the results of coabatement rates of SO_2, NO_X, and $PM_{2.5}$ from CO_2 mitigation, broken down by location and mitigation option type.

From the national average perspective, it is shown from Table 6 that for each gigaton (GT) of CO_2 reduction in China's power generation sector in 2010, 2.23 MT of SO_2, 2.06 MT of NO_X and 0.36 MT of $PM_{2.5}$ will be reduced simultaneously. As in 2010 the total CO_2 emissions from China's power generation sector were about 3.5 GT, and the SO_2, NO_X, and $PM_{2.5}$ emissions after control were respectively 7.22 MT, 13.19 MT, and 1.54 MT, it can be estimated that in 2010, each 1% of CO_2 reduction in China's power generation sector will result in the coreduction of 0.078 MT of SO_2, 0.072 MT of NO_X, and 0.012 MT of $PM_{2.5}$, respectively, which were 1.1%, 0.5%, and 0.8% of corresponding pollutants in this sector. It is worthy to note that these relative coabatement rates (1% of CO_2 reduction vs 1.1% of SO_2 reduction) will be time-varying values because the absolute coabatement rates (such as 2.46 $tSO_2/ktCO_2$) will change; the CO_2 emissions, as well as the SO_2, NO_X, and $PM_{2.5}$ emissions after control will also change.

Table 6. Co-Abatement Rates of SO_2, NO_X, and $PM_{2.5}$ from CO_2 Mitigation, Broken down by Location and Mitigation Option Type

		co-abatement rates		
		$tSO_2/ktCO_2$	$tNO_X/ktCO_2$	$tPM_{2.5}/ktCO_2$
by location	north	2.46	2.49	0.36
	northeast	2.07	2.33	0.49
	east	1.45	1.25	0.36
	central	2.21	1.90	0.35
	northwest	2.63	2.37	0.29
	south	2.20	1.86	0.36
by mitigation option type	hydro	2.34	2.06	0.35
	wind	2.76	2.77	0.42
	biomass	1.46	0.48	0.24
	solar PV	2.19	1.96	0.26
	fuel switch	0.79	0.73	0.29
national average		2.23	2.06	0.36

From a regional perspective, the East China grid's coabatement rates are comparatively lower than other regions, which corresponds to a higher deployment level of pollutant control equipment in this economically developed area. As for the regional coabatement rate for each type of pollutant, for each 1000 tons of CO_2 reduced, the Northwest China grid has the highest SO_2 coabatement rate (2.63t), the North China grid has the highest NO_X coabatement rate (2.49t), and the Northeast China grid has the highest $PM_{2.5}$ coabatement rate (0.49t).

From a mitigation option perspective, the wind power technology has the highest coabatement rates for all three types of conventional pollutants. For each 1000 tons of CO_2 reduced, the wind power technology can reduce 2.76 tons of SO_2, 2.77 tons of NO_X and 0.42 tons of $PM_{2.5}$. Hydro and solar PV technologies follow wind power technology. Fuel switch from coal to natural gas has relatively small advantage in reducing the conventional air pollutants. It is also noted that biomass has the lowest coabatement rates in NO_X and $PM_{2.5}$, compared to all other options. The above information can lay an important foundation for making comprehensive pollutants control strategies for China. Considering only the cobenefits perspective (ignoring other factors such as cost and technical barriers), it is suggested that China should greatly promote wind, hydro and solar PV technologies. They are the wisest choices for high-efficient coabatement of CO_2 and conventional pollutants.

Specific to each region, different types of technologies are suggested for achieving the maximum coabatement of pollutants. For the North, Northeast, Central, and Northwest China grids, wind power has the most significant coabatement effects, followed by hydro power. For the East China grid, wind power, solar PV, and hydro power are almost equally matched. For the South China grid, solar PV is the technology with the most significant coabatement effects, followed by wind and hydro power. The main reasons for these differences are the variety of regional energy structure and the disparities in the deployment level of pollutant control technologies. Compared to national-level judgment, this information can give more specific references to the regional decision-making in terms of comprehensive pollution control.

5.3. Future Applications of This Methodology. This paper developed a combined margin methodology to quantify baseline emission factors of air pollutants in China's regional power grids. Quantifying the baseline emission factors is only one goal of this study. The methodology developed here deserves more attention. It points out the inaccuracy of evaluating a technology's mitigation effects using only one specific technology as the reference. It allows the convenient annual update on the status quo of in-use mitigation technologies and therefore can timely evaluate the baseline emission factors of the grids. It also unifies the methodologies of quantifying baseline emission factors of air pollutants and CO_2 in the power sector, and can be widely used by other countries (which are suitable for simple OM method in CDM). It is believed that this methodology can be helpful for decision-makers in developing scientific, comprehensive air pollution control strategies. Moreover, given that CDM EB is encouraging project participants to voluntarily describe the cobenefits of their projects,[21] this methodology can also contribute to the discussions on how to quantify the sustainable development cobenefits and how to include them in CDM approval process in the future.

ASSOCIATED CONTENT

Supporting Information

We provide list of symbols, important data sources and figures for sensitivity analysis. This material is available free of charge via the Internet at http://pubs.acs.org.

AUTHOR INFORMATION

Corresponding Author

*Phone: +86 10 62794115; e-mail: canwang@tsinghua.edu.cn.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

We gratefully acknowledge the comments and suggestions from anonymous reviewers. This research was funded jointly by the China Postdoctoral Science Foundation (No. 023203091) and the National Natural Science Foundation of China (No.71273153). We are also grateful to Mr. Liyang Wan for his help in ArcGIS, and to Ms. Marina Brenden for her great efforts in improving the language of this paper.

REFERENCES

(1) ACM0002: Consolidated Baseline Methodology for Grid-Connected Electricity Generation from Renewable Sources–Version 13.0.0. CDM–Executive Board: Bonn, 2012; http://cdm.unfccc.int/methodologies/DB/UB3431UT9I5KN2MUL2FGZXZ6CV71LT (accessed 26 November, 2011).

(2) Marnay, C.; Fisher, D.; Murtishaw, S.; Phadke, A.; Price, L.; Sathaye, J. *Estimating Carbon Dioxide Emissions Factors for the California Electric Power Sector*, report LBNL-49945; Lawrence Berkeley National Laboratory: Berkeley, CA, 2002; http://industrial-energy.lbl.gov/node/148.

(3) Bettle, R.; Pout, C. H.; Hitchin, E. R. Interactions between electricity-saving measures and carbon emissions from power generation in England and Wales. *Energy Policy.* **2006**, *34*, 3434–3446.

(4) Siler-Evans, K.; Azevedo, I. L.; Morgan, M. G. Marginal emissions factors for the U.S. electricity system. *Environ. Sci. Technol.* **2012**, *46*, 4742–4748.

(5) Arnann, M.; Bertok, I.; Borken, J.; et al. *GAINS-Asia: A Tool to Combat Air Pollution and Climate Change Simultaneously*; IIASA and Other Cooperating Agencies: Laxenburg, 2008; http://www.iiasa.ac.at/rains/reports/Asia/GAINS-Asia-Methodology.pdf (accessed 29 November, 2011).

(6) Rive, N.; Aunan, K. Quantifying the air quality cobenefits of the clean development mechanism in China. *Environ. Sci. Technol.* **2010**, *44*, 4368–4375.

(7) Zhang, C. Y. Studies on present and future emissions of PM, SO_2, NO_X. Master Thesis, Tsinghua University, Beijing, 2008.

(8) *2011 Emission Coefficients—The Calculation Process of BM*; National Development and Reform Commission: Beijing, 2011; http://cdm.ccchina.gov.cn/WebSite/CDM/UpFile/File2719.doc (accessed March 2, 2012).

(9) China Electricity Yearbook Editorial Board. *China Electricity Yearbooks (2007–2011)*; China Electricity Press: Beijing, 2008–2012.

(10) *Electric Power Industry Statistical Information Compilation (2008–2010)*; China Electricity Council: Beijing, 2009–2011.

(11) Department of Environmental Science and Engineering. *Deciding the Limits of Sulfur and Ash Contents of Coal Mined and Coal Washed*; Tsinghua University: Beijing, 1997.

(12) SO_2NO_XThe Water Content, Ash Content and Volatile in Commercial Coal; http://www.ecoalchina.com/knowleage/mtzs/jczs/mtsx/656061.shtml.

(13) Standards Division of State Environmental Protection Bureau. *Manual of Industrial Pollutants Production and Emission Factors*; Chinese Environmental Science Press: Beijing, 1996.

(14) Zhang, Q. *Regional Particles Emissions and Simulation Researches in China*. Doctoral Dissertation, Tsinghua University, Beijing, 2005.

(15) *Compilation of Air Pollutant Emission Factors*; United States Environmental Protection Agency: Washington, DC, 1995; http://www.epa.gov/ttn/chief/ap42/index.html.

(16) *List of Desulphurization Facilities in Operation in Coal-Fired Units 2008–2010*; Ministry of Environmental Protection in China: Beijing, 2008–2010; http://www.sepa.gov.cn/info/bgw/bgg/200906/W020090622322728172874.pdf. http://www.mep.gov.cn/pv_obj_cache/pv_obj_id_7D33A4EEB3264BBA9C70845BC2D5A702F5980500/filename/W020100326526568136035.pdf. http://www.mep.gov.cn/pv_obj_cache/pv_obj_id_D6D6A66BDACA5D41865387A4A378EE78CC6D0900/filename/W020110420407642353906.pdf.

(17) *List of Denitrification Facilities in Operation in Coal-Fired Units 2010*; Ministry of Environmental Protection in China: Beijing, 2011; http://www.mep.gov.cn/pv_obj_cache/pv_obj_id_BDBA739F7ABE657A4B5B0C783AB35F1B23100300/filename/W020110420407642383272.pdf.

(18) Tan, Q.; Feng, Y. C. Status and prospects of china's flue gas denitrification industry and the research progress for SCR $DeNO_X$ catalysts. *Chem. Ind. Eng. Prog.* **2011**, *30*, 709–713.

(19) *Briefing on the Energy Saving and Emission Reduction Work in China's Power Generation Sector in 2008*; China Electricity Regulatory Commission: Beijing, 2009; www.serc.gov.cn/ywdd/200911/W020091102328545684394.doc (accessed April 13, 2012).

(20) China Environmental Statistics Yearbook Editorial Board. *China Environmental Statistics Yearbooks (2009–2011)*; China Statistics Press: Beijing, 2009–2011.

(21) Highlights—70th meeting of the CDM Executive Board. https://cdm.unfccc.int/CDMNews/issues/issues/I_E3F9IG2J6WKDP6N9DQDPAIXB1LFO9E/viewnewsitem.html (accessed November 28, 2012).