Environmental Generation Scheduling Considering Air Pollution Control Technologies and Weather Effects

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***Abstract*—Because the power industry makes a significant contribution to air pollution, a variety of air pollution control technologies have been adopted to reduce emissions of nitrogen oxides, sulfur dioxide, and particulate matters. However, the deployment of these technologies affects the operation of the power plants and of the power system. This paper first discusses the emissions of multiple pollutants by coal- and gas-fired generators equipped with different emission control devices. It then presents the formulation of an environmental power generation scheduling (EnPGS) model, which coordinates the operating cost and the emissions of these pollutants, including the emissions during the startup and shutdown processes. This model considers the air quality index and how this index is affected by the weather, and optimizes the spatial distribution of generation between regions. It also takes into account the operating characteristics of various emission control devices, such as the deactivation of selective catalytic reduction at low output, and the burn mode switching of combined cycle gas turbines. A case study covering several Chinese provinces demonstrates the potential effectiveness of the EnPGS at reducing multiple air pollutants.**

***Index Terms*—Air pollution control technology, air quality, environmental dispatch, generation scheduling, weather effect.**

I. Introduction

AIR pollution is endangering the health of residents of major cities in China. In 2013, emissions of nitrogen oxides (NO_x), sulfur dioxide (SO_2), and particulate matters (PM) reached 20.44, 22.27 and 15 million tons, making China the largest emitter in the world. These air pollutants may shorten life expectancy by five life years [1].

The power sector is one of the major sources of the pollutants, contributing 53% of anthropogenic emissions of SO_2, 36% of NO_x and 9% of PM in China [2]. Coal, gas, oil, and biomass power plants all contribute to these pollutants. Mitigating measures, including strict emission standards and penalties, the deployment of various air pollution control technologies, and the setting of regional targets for emission reductions, have been imposed to reduce emissions. The air quality index (AQI) has become an important way of measuring and reacting to episodes of serious pollution. It is calculated using the procedure described in [3] and is based on the highest value of the normalized (adjusted by related standards) concentration of each pollutants (including SO_2, NO_x, CO, PM2.5, PM10 and Ozone). Currently AQI can be forecasted 72 h ahead [4], [5]. Different levels of alerts are issued by the government based on the forecasted AQI. Corresponding emission control targets are suggested for different industries, and these will become mandatory in the near future [6]. This paper discusses the challenges that these measures represent for the operation of the power system and how these challenges might be met.

Firstly, various air pollution control technologies have already been deployed. In 2014, over 60% of coal-fired generators were equipped with low NO_x burners (LNB) and selective catalytic reduction (SCR) devices. Recently, new clean coal technologies, called "near zero emission" (NZE), have been deployed [7]. NZE refers to coal-fired generators that meet the national emission standards of combined cycle gas turbines (CCGTs) by upgrading emission control devices. The main NZE techniques include increasing the efficiency of the flue gas desulfurization (FGD) system, improving the LNB and the electrostatic precipitators (ESP), adding wet scrubbers, etc. Such NZE technologies have already been installed in several thermal power plants in the coastal area. Depending on the air pollution control technologies that have been deployed, the emissions produced by different generators can vary significantly. However, these air pollution control technologies increase the complexity of power generation scheduling. For example, when a generator operates at low power output, its SCR must be shut down for technical reasons, and the NO_x emissions increase significantly.

Secondly, the government has begun collecting, monitoring and storing emissions data with at least an hourly resolution for almost all power plants in China. These data are used to enforce strict emission standards and impose tiered emission penalties. In Beijing, the average emission penalty has been increased by a factor of 15 since January 1, 2014. In Shanghai, the emission penalty rate for NO_x was \$0.20/kg before 2014. In 2015, it was raised by 217% to \$0.65/kg, and will be around \$1.45/kg in 2019. Besides, tiered emission penalties have been

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set. For example, in Beijing, the emission penalty rates of SO_2 and NO_x are 0.8, 1.6 and \$3.2/kg when the actual emissions are less than 25 mg/Nm^3, between 25 and 50 mg/Nm^3, and above 50 mg/Nm^3, respectively.

Thirdly, since the AQI is based on the concentration of pollutants in the air, additional emissions further deteriorate the AQI in the following periods. Moreover, a bad AQI always results from bad conditions for the diffusion of pollutants. Emissions during bad AQI periods will therefore further degrade air quality [8]. Emission constraints related to AQI may therefore have to be imposed on the operation of power systems in different regions. The worse the pollutant level is, the fewer additional emissions are allowed. However, since the power plants located in different cities are connected by the transmission network and since the system operator optimizes the generation schedule for all the power plants, the differences in AQI in different cities could be coordinated. This is particularly useful if these cities are located downstream from each other in a prevailing wind corridor.

NO_x emissions were first studied in environmental economic dispatch (EED) models, and treated either as objective [9] or constraints [10]. NO_x emissions were also considered in optimal power flow [11], [12]. Venkatesh *et al.* [13] proposed a model that minimizes the operating cost and non-specific emissions. A few papers [14]–[16] dealt with emissions of multiple pollutants (e.g. NO_x, SO_2, etc.) by creating an objective function where each pollutant is weighted by a measure of the degree to which it harms the environment. A couple of studies have recently considered the effects of PM emissions [17], [18]. The emissions of NO_x and SO_2 by coal-fired generators during startup were examined in details in [19]. The authors of [20] proposed a three-area EED model. In summary, previous publications have investigated how emissions can be factored into the power generation scheduling problem. However, the operating characteristics of various air pollution control technologies have not been integrated in these formulation and the effect of the weather is not considered either.

This paper proposes an environmental power generation scheduling (EnPGS) model to coordinate emissions of multiple pollutants over different areas, considering the air quality. Using actual monitoring data from power plants, Section II describes how the emissions of NO_x, SO_2 and PM pollutants can be modeled during normal operation as well as during startup and shutdown. These models take into account the operational characteristics of the following air pollution control technologies: LNB, SCR, selective non-catalytic reduction (SNCR), FGD, and ESP. Complex mechanisms, such as the deactivation of SCR at low power output and the combustion mode switching of CCGTs are considered. The emission of carbon dioxide (CO_2) by power plant also has an important environmental impact. However, because CO_2 is a greenhouse gas and not a conventional pollutant, it is not incorporated into the definition of AQI. CO_2 is therefore not considered in the EnPGS model.

Section III presents the EnPGS formulation and discusses how it optimizes generation scheduling over a multi-city interconnected regional power system, taking into account weather-dependent local emission constraints, and the AQI in different cities.

Section IV illustrates the proposed approach using the power grid of Northern China as a case study. This grid covers the cities of Beijing and Tianjin as well as the provinces of Hebei and Inner Mongolia. Based on AQI data, some typical weather scenarios are analyzed to demonstrate the effect of weather conditions on the optimal generation schedule.

II. Emissions Considering Air Pollution Control Technologies

This section formulates the emission characteristics of coal-fired and gas-fired generators and the effect of the main air pollution control technologies. Due to space limitations, it is not possible to include less prevalent types of generators.

A. Coal-Fired Generators

1) Emissions in Operation:

a) NO_x: Without air pollution control devices, NO_x emissions are strongly related to the output of a generator [21], and can be represented by a quadratic function of this power output [10], [19]:

$$e_0^{\mathrm{NO_x}} = (a^N P^2 + b^N P + c^N)Z \tag{1}$$

where $e_0^{\mathrm{NO_x}}$ is the NO_x emissions without air pollution control devices, P is the power output of the generator, Z indicates the status of the generator, and a^N, b^N, c^N are coefficients, whose value varies from generator to generator and depends on the boiler and fuel. While other formulations of NO_x emissions have been proposed [11], [22], [23], this paper uses a quadratic polynomial function because it provides a better fit to actual monitoring data from several power plants in China. However, the proposed EnPGS formulation can accommodate these alternative formulations.

LNB is a low-cost method to reduce excess air and achieve a lower combustion temperature, resulting in lower emission of NO_x. Since this technology can reduce NO_x emissions by about 30% [24], most coal-fired generators in China are now obliged to install LNB. SCR is another common denitration technology, which adds ammonia $(\mathrm{NH_3})$ in the flue to transform the nitrogen oxides to harmless molecular nitrogen and water vapor. While the efficiency of an SCR denitrator is affected by many factors, it can be controlled by adjusting the amount of ammonia injected into the flue. Thus, the denitration efficiency of a specific SCR device can be taken as having a constant value in the 80–90% range. If the generator is running at a low power output, the flue temperature can drop below 300 °C. However, this chemical denitration reaction requires an operating temperature between 300 and 410 °C in order to maintain the activity of the catalyst (such as $\mathrm{TiO_2}$, $\mathrm{V_2O_5}$, or $\mathrm{WO_3}$). To avoid releasing ammonia in the atmosphere, the SCR device must therefore be shut down when the unit's power output drops below a certain threshold P^s.

The NO_x emissions of a coal-fired generator with LNB and SCR denitrator can therefore be formulated as:

$$e^{\mathrm{NO_x}} = \begin{cases} (1-\eta)\lambda \times e_0^{\mathrm{NO_x}}, & P \geq P^s \\ \lambda \times e_0^{\mathrm{NO_x}}, & P < P^s \end{cases} \tag{2}$$

where $e^{\mathrm{NO_x}}$ is the NO_x emission, λ represents the effectiveness of the LNB, η is the SCR efficiency, and P^s is the threshold below which the SCR cannot operate.

SNCR uses ammonia or urea without catalyst and reduces NO_x emissions by 30–70%. SNCR is cheaper and is always implemented on smaller generators. Its effectiveness can be formulated in a similar way as for the SCR.

b) SO_2: A quadratic function can also be used for the SO_2 emissions [23], [25]:

$$e_0^{\mathrm{SO_2}} = (a^S P^2 + b^S P + c^S)Z \tag{3}$$

where $e_0^{\mathrm{SO_2}}$ is the SO_2 emission without air pollution control devices. a^S, b^S, c^S are coefficients which depend mainly on the generator type and the sulphur content of the coal.

FGD has been widely adopted in China. The SO_2 emissions with FGD devices can be expressed as follows:

$$e^{\mathrm{SO_2}} = (1-\gamma) \times e_0^{\mathrm{SO_2}} \tag{4}$$

where $e^{\mathrm{SO_2}}$ is the actual SO_2 emission, γ is the desulfurization efficiency, which ranges from 90% to 95%.

c) PM: Most of the mineral content of the fuel is transformed into ash during burning. PM emissions have not been extensively discussed in the literature. Based on actual monitoring data, PM emissions can also be formulated using a quadratic function:

$$e_0^{\mathrm{PM}} = (a^P P^2 + b^P P + c^P)Z \tag{5}$$

where e_0^{PM} is the PM emissions without air pollution control devices, and a^P, b^P, c^P are coefficients.

ESP utilizes electrostatic forces to facilitate the collection of particles [17]. This device has been installed in 94% of coal-fired generators in China. The ESP removal efficiency ranges from 95% to 99.9%. Since this efficiency decreases slightly as the power output increases, PM emissions can be formulated as follows:

$$\begin{aligned} e^{\mathrm{PM}} &= (1-\mu) \times e_0^{\mathrm{PM}} \\ \mu &= \upsilon P/P_{\max} + \mu_m \end{aligned} \tag{6}$$

where e^{PM} is the actual PM emission, μ is the dust removing efficiency, $P_{\max}$ is the maximum power output, υ and μ_m are parameters, with $\upsilon < 0$.

2) Emissions During Startup and Shutdown: The startup and shutdown processes of coal-fired generators requires 4–20 h [19], [26]. Although the power output is quite low during startup and shutdown compared to the normal operating state, the concentration of the emissions is relatively high, as some of the air pollution control devices are not in service [19]. Because of the increasing amount of intermittent wind and solar power being produced, conventional generators are likely to be turned on and off much more frequently, and emissions during startup and shutdown could become more significant.

Generally, the startup process consists of four steps: ignition, acceleration to synchronous speed, synchronization with the grid, and ramping up to minimum stable generation. While electric power is generated from the instant of synchronization, emissions start from the very first step. The shutdown process is similar but usually shorter. First, the power output is gradually reduced to zero. The generator is then separated from the grid, at which point the emissions drop quickly to zero.

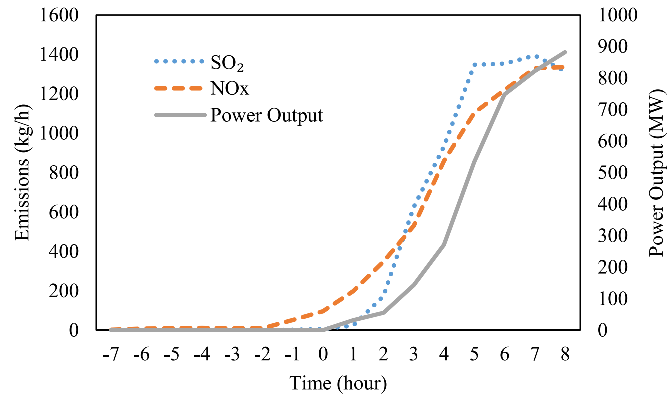

Fig. 1. Startup power output and emissions of a coal-fired generator.

Binary variables $Z_{u,t}$, $Y_{u,t}^{+}$ and $Y_{u,t}^{-}$ are used to describe the status of a generator. $Z_{u,t} = 1$ indicates that the generator operates in the normal state. $Y_{u,t}^{+}$ equals 1 only at the end of the startup procedure. $Y_{u,t}^{-}$ equals 1 only at the beginning of the shutdown procedure. The relation between $Y_{u,t}^{+}$, $Y_{u,t}^{-}$ and $Z_{u,t}$ is discussed in [27], and can be summarized as follows:

$$Z_{u,t-1} + Y_{u,t}^{+} - Y_{u,t}^{-} - Z_{u,t} = 0 \tag{7}$$

$$Y_{u,t}^{+} + Y_{u,t}^{-} \leq 1 \tag{8}$$

Fig. 1 shows how emissions evolve during startup based on data from [26]. For a given generator *u*, the power output and the emission profile during each startup process are similar and can be represented by $p_{u,k}^{\mathrm{st}}(k)$ and $e_{u,k}^{\mathrm{st},x}(k)$, where *k* is a time parameter indicating the time until the end of startup. FGD and ESP can be put into operation soon after startup, but SCR cannot [19]. For each coal-fired generator, the power output and emissions during startup can thus be expressed as follows:

$$P_{u,t}^{\mathrm{st}} = \sum_{k=1}^{SD_1} p_{u,k}^{\mathrm{st}} Y_{u,t+k}^{+} \tag{9}$$

$$es_{u,t}^{x} = \sum_{k=1}^{SD_0} e_{u,k}^{\mathrm{st},x} Y_{u,t+k}^{+} \tag{10}$$

where

- $P_{u,t}^{\mathrm{st}}$ startup power output of generator *u* at time *t*;
- $p_{u,k}^{\mathrm{st}}$ startup output curve for generator *u*;
- SD_1 startup duration from synchronization until minimum stable generation is reached;
- SD_0 startup duration from ignition to minimum stable generation (SD_0 is longer than SD_1.);
- $es_{u,t}^{x}$ emission of *x* by generator *u* at time *t*;
- $e_{u,k}^{\mathrm{st},x}$ startup emission curve of *x* for generator *u*;
- x NO_x, SO_2, or PM.

Note that $p_{u,k}^{\mathrm{st}}$ and $e_{u,k}^{\mathrm{st},x}$ are given parameters, but $P_{u,t}^{\mathrm{st}}$ and $es_{u,t}^{x}$ are decision variables.

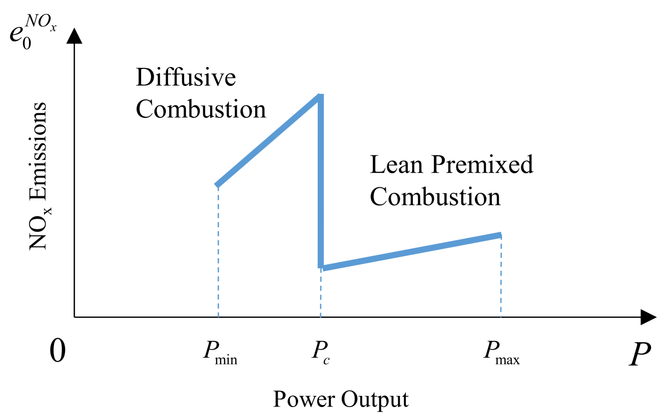

Fig. 2. NO_x emissions for a CCGT with lean premixed combustion mode and diffusive combustion mode.

The power output and emissions during shutdown are formulated as follows:

$$P_{u,t}^{\mathrm{ct}} = \sum_{k=1}^{CD_1} p_{u,k}^{\mathrm{ct}} Y_{u,t-k}^{-} \tag{11}$$

$$ec_{u,t}^{x} = \sum_{k=1}^{CD_0} e_{u,k}^{\mathrm{ct},x} Y_{u,t-k}^{-} \tag{12}$$

where

$P_{u,t}^{\mathrm{ct}}$ shutdown power output of generator *u* at time *t*;

$p_{u,k}^{\mathrm{ct}}$ shutdown output curve for generator *u*;

CD_1 shutdown duration from reducing power to separating from the grid;

CD_0 shutdown duration from reducing power to completely off;

$ec_{u,t}^{x}$ shutdown emission of *x* by generator *u* at time *t*;

$e_{u,k}^{\mathrm{ct},x}$ shutdown emission curve of *x* for generator *u*.

Note that in $p_{u,k}^{\mathrm{ct}}$ and $e_{u,k}^{\mathrm{ct},x}$, k represents the time duration since the *beginning* of the shutdown process.

B. Gas-Fired Generators

The main emissions from CCGT plants are NO_x, but their concentration is only 10–15% of what it would be if the power were produced by a coal-fired generator of similar capacity. Since the concentration of SO_2 emissions is always less than 1 mg/Nm^3, and 2 mg/Nm^3 for PM, emissions of SO_2 and PM by CCGT plants will not be considered in this paper.

1) Emissions in Operation: Most CCGTs in China have installed LNB to reduce NO_x emissions. Some have also installed SCR for better emission performance. As with coal-fired generators, the SCR cannot operate below a certain threshold of power output. However, for CCGTs the switching of combustion mode should also be considered, because it has a significant impact on the NO_x emissions. When a CCGT runs at a high power output, it operates with a lean premixed combustion mode. However, this lean premixed combustion mode results in combustion instabilities at low power outputs. As shown in Fig. 2, the CCGT must then switch to a diffusive combustion mode, where the NO_x emissions are much higher.

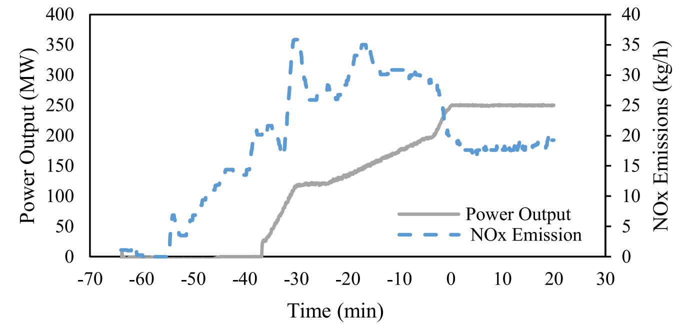

Fig. 3. Startup power output and emissions of a CCGT.

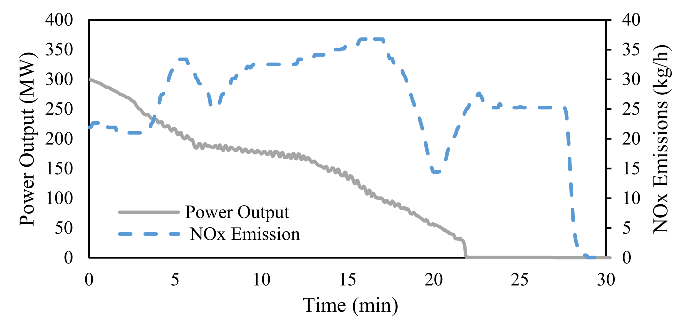

Fig. 4. Shutdown power output and emissions of a CCGT.

Equation (13) thus describes the NO_x emissions of a CCGT, where b_p and b_d correspond to the lean premixed and diffusive combustion modes. P_c is the critical power output, which is about 65–70% of the rated capacity.

$$e_0^{\mathrm{NO_x}} = \begin{cases} b_p P, & P \geq P_c \\ b_d P, & P < P_c \end{cases} \tag{13}$$

2) Emissions During Startup and Shutdown: The emissions of CCGTs during startup and shutdown processes are similar to those of coal-fired generators, but with much shorter durations. Figs. 3 and 4 show the power output and the NO_x emissions of a CCGT during startup and shutdown based on actual monitoring data. The time required for startup is 1 to 2 h and 0.5 h for shutdown.

Since the profiles of power output and emissions during startup and shutdown are similar to those of coal-fired generators, Eqs. (7)–(12) are applicable, albeit with different parameters.

III. EnPGS Model

This section formulates the EnPGS model based on the air pollution control technology formulation discussed above. Weather-dependent local emission constraints and tiered emission penalties are also considered. The Independent System Operator (ISO) would run the EnPGS model to determine the power generation schedules.

A. Decision Variables

Binary variables include the hourly unit status $Z_{u,t}$, the unit startup $Y_{u,t}^{+}$ and the unit shutdown $Y_{u,t}^{-}$. The subscripts *u* and *t* denote respectively the unit and the time interval.

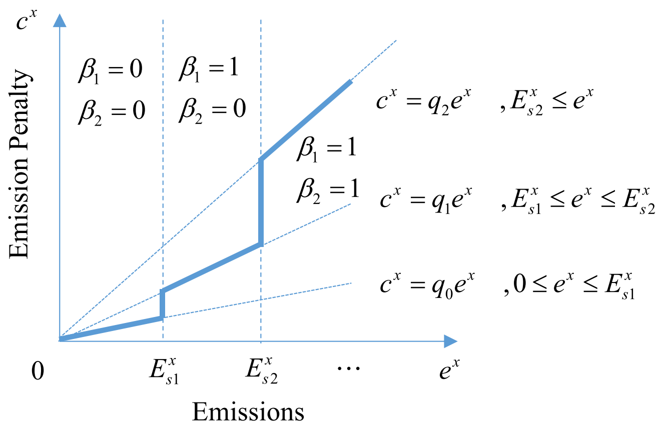

Fig. 5. Typical emission penalty function.

Continuous variables include the power output during operation $P_{u,t}$, the power output during startup $P_{u,t}^{\mathrm{st}}$, the power output during shutdown $P_{u,t}^{\mathrm{ct}}$, along with the emissions during operation $e_{u,t}^x$, during startup $es_{u,t}^x$, and shutdown $ec_{u,t}^x$. The superscript *x* denotes NO_x, SO_2 or PM.

B. Objective Function

The goal of conventional power system generation scheduling is to minimize the total operating cost. However, in this case the objective function must include not only the running, startup and shutdown cost, but also the emission penalties. The maintenance cost is included in the running cost. Since this formulation is used for day-ahead scheduling, investments and other fixed costs are not included in the objective function.

$$\min z = \sum_{u=1}^{N_u}\sum_{t=1}^{N_t} F_{u,t} + \sum_{u=1}^{N_u}\sum_{t=1}^{N_t}\left(p_u^{Y+}Y_{u,t}^{+} + p_u^{Y-}Y_{u,t}^{-}\right) + \sum_{x}\sum_{u=1}^{N_u} c^x\left(\sum_{t=1}^{N_t} e_{u,t}^x\right) \tag{14}$$

where $F_{u,t}$ is the variable cost of generator *u* at time *t*, p_u^{Y+} and p_u^{Y-} represent the startup and shutdown costs, $Y_{u,t}^{+}$ and $Y_{u,t}^{-}$ are binary variables representing the startup and shutdown status of a generator, $e_{u,t}^x$ is the emission rate of pollutant *x*, $c^x(e^x)$ is the emission penalty function of pollutant *x*. This penalty function is piecewise linear with *m* segments $(m \geq 1)$:

$$\begin{cases} c^x = q_0 e^x, & 0 \leq e^x < E_{s1}^x \\ c^x = q_1 e^x, & E_{s1}^x \leq e^x < E_{s2}^x \\ \cdots & \\ c^x = q_{m-1} e^x, & E_{s(m-1)}^x \leq e^x \end{cases} \tag{15}$$

where c^x is the emission penalty, e^x is the emission of pollutant *x* during normal operation. $q_i(0 \leq i \leq m-1)$ is the emission penalty rate for corresponding emission level, and $E_{si}^x(i = 1, 2, \cdots)$ is the emission level boundary.

Fig. 5 shows a three-segment example of a tiered emission penalty function.

TABLE I
EMISSION CONTROL TARGET FACTORS

AQI	Air Pollution Level	Emission Control Target Factor $Ef_{a,t}^x$
0–50	Good	1
51–100	Moderate	0.95
101–150	Unhealthy for sensitive groups	0.9
151–200	Unhealthy	0.85
201–300	Very unhealthy	0.8
>300	Hazardous	0.7

Equation (15) can be formulated as (16):

$$\begin{cases} c^x \geq q_0 e^x \\ c^x - q_1 e^x + M(1-\beta_1) \geq 0 \\ E_{s1}^x - e^x + M\beta_1 \geq 0 \\ \cdots \\ c^x - q_{m-1} e^x + M(1-\beta_{m-1}) \geq 0 \\ E_{s(m-1)}^x - e^x + M\beta_{m-1} \geq 0 \end{cases} \tag{16}$$

where *M* is a large number. $\beta_i(1 \leq i \leq m-1)$ is a binary variable indicating the generator emission level. If current emissions are in the *j*th segment $(1 \leq j \leq m)$, for $1 \leq i \leq j-1$, $\beta_i = 1$; for $j \leq i < m-1$, $\beta_i = 1$, as shown in Fig. 5.

C. Constraints

Constraints on the EnPGS include emission control requirements, generator operational limits, and unit commitment constraints.

1) Regional Emission Constraints:

$$\sum_{u\in a} \tilde{e}_{u,t}^x \leq E_{a,t}^{x,\max} \tag{17}$$

where $E_{a,t}^{x,\max}$ is the maximum emission of pollutant *x* in area *a* at time *t*. The emission control targets are set on a regional basis and depend on the AQI forecasts for each region:

$$E_{a,t}^{x,\max} = Eb_a^x \times Ef_{a,t}^x \tag{18}$$

where Eb_a^x is the emission control base target, which is determined by the area diffusion condition and policy and does not vary with weather. $Ef_{a,t}^x$ is the emission control target factor, which is set according to the air pollution level based on AQI forecast, as provided in Table I.

$\tilde{e}_{u,t}^x$ is the total emission of pollutant *x*, including emissions during normal operation $e_{u,t}^x$, as well as during the startup and shutdown processes, $es_{u,t}^x$ and $ec_{u,t}^x$:

$$\tilde{e}_{u,t}^x = e_{u,t}^x + es_{u,t}^x + ec_{u,t}^x \tag{19}$$

$e_{u,t}^x$ is determined using Eqs. (1)–(6), while $es_{u,t}^x$ and $ec_{u,t}^x$ are determined by Eqs. (10) and (12).

2) Forced Exit of SCR: The deactivation of SCR as defined by (2) involves an "if-else" formulation that can be translated into the following two-segment piecewise formulation:

$$\begin{cases} e_{u,t}^{\mathrm{NO_x}} \geq e_{1,u}^{\mathrm{NO_x}}(P_{u,t}) \\ e_{u,t}^{\mathrm{NO_x}} - e_{0,u}^{\mathrm{NO_x}}(P_{u,t}) + M\alpha_{u,t}^{(1)} \geq 0 \\ P_{u,t} - P_u^s + M(1-\alpha_{u,t}^{(1)}) \geq 0 \end{cases} \tag{20}$$

where $\alpha_{u,t}^{(1)}$ is a binary variable which equals 1 when the power output $P_{u,t}$ exceeds the threshold P_u^s. $e_{1,u}^{\mathrm{NO_x}}(P_{u,t})$ and $e_{0,u}^{\mathrm{NO_x}}(P_{u,t})$ are the emission characteristics at high and low power output, respectively. This formulation technique is very similar to that of (15) and (16).

3) CCGT Combustion Mode Switch: The CCGT $\mathrm{NO_x}$ emissions with combustion mode switching are described by (13), which is implemented using the technique of (20).

4) Generator Variable Operation Cost: The variable cost of generators in operation is:

$$F_{u,t} = (a_u^F P_{u,t}^2 + b_u^F P_{u,t} + c_u^F) Z_{u,t} \tag{21}$$

where $F_{u,t}$ is the variable cost in operation, $P_{u,t}$ is the power output, $Z_{u,t}$ is the unit status, and a_u^F, b_u^F, and c_u^F are coefficients.

5) Generator Startup and Shutdown: The generator startup and shutdown power outputs, $P_{u,t}^{\mathrm{st}}$ and $P_{u,t}^{\mathrm{ct}}$, are given by Eqs. (9) and (11).

The real power output $P_{u,t}^{\sim}$ is the aggregate of the power output in normal operation $P_{u,t}$, the power output during startup $P_{u,t}^{\mathrm{st}}$, and the power output during shutdown $P_{u,t}^{\mathrm{ct}}$:

$$P_{u,t}^{\sim} = P_{u,t} + P_{u,t}^{\mathrm{st}} + P_{u,t}^{\mathrm{ct}} \tag{22}$$

6) Generation Load Balance: The sum of the real power outputs must be equal to the load at all time periods:

$$\sum_u P_{u,t}^{\sim} = \sum_d D_{d,t} \tag{23}$$

where $D_{d,t}$ is the *d*th demand at time *t*.

Other unit commitment constraints, including generator power output range, ramping, system reserve, transmission network constraints, fuel supply constraints are implemented as described in [28] and [29].

As formulated above, the EnPGS is a quadratically constrained mixed integer program problem, which can be solved using standard optimization software, such as GAMS [30].

IV. Case Study

The proposed EnPGS was applied to the North China Regional Power System.

A. Basic Data

This model contains 157 generators, 1,328 buses and 1,725 branches. Sixteen of these generators are CCGTs and the remaining ones are coal-fired. The generators are located in four areas, namely Beijing (BJ), Tianjin (TJ), Hebei (HB), and Inner Mongolia (IM). Fig. 6 shows the geographical relationships and principal electrical interconnections between these four areas. Table II gives the capacity, number of generators and associated air pollution control technologies. Generally, BJ and TJ import power from HB and IM. BJ, TJ and IM are connected to HB with sufficient tie lines. January 16, 2015 is used to test the proposed model because the AQI varied greatly on that day. The maximum load for BJ, TJ, and HB is 37,938 MW. Several large, base generation coal plants are located in IM, but the load in that region is not taken into account.

The efficiency of SCR is assumed to be 85%, and its deactivation takes place when the power output is less than 50% of rated capacity.

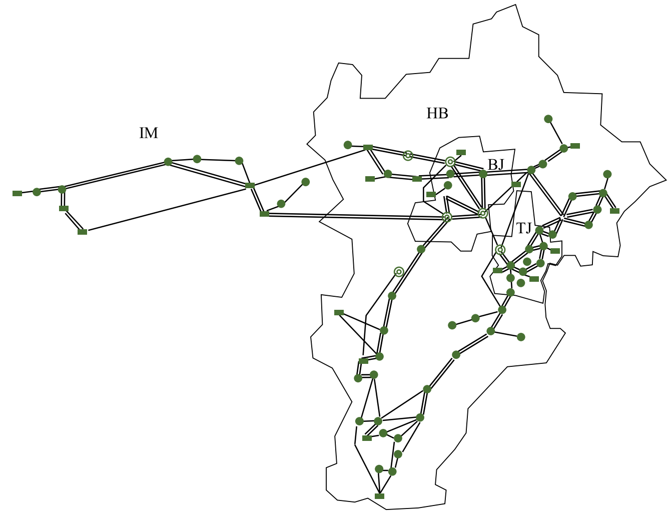

Fig. 6. Geographical relationships and electrical interconnections.

TABLE II
Basic Information About the Generators

Area	Fuel	No. of Gens	No. of LNB	No. of SCR	No. of FGD	No. of ESP	Capacity (MW)
BJ	Coal	17	17	14	17	4	3,335
BJ	Gas	13	13	4	0	0	3,919
TJ	Coal	20	20	11	20	0	6,024
TJ	Gas	3	1	1	0	0	265
HB	Coal	70	70	32	63	0	21,280
IM	Coal	34	34	14	20	0	18,080

TABLE III
Emission Penalty Rates in China

Segment	Emission Level	Emission Penalty Rate Factor
0	0–50%	0.5
1	50–100%	1
2	>100%	2

TABLE IV
Emission Penalty Base Prices

Area	$\mathrm{NO_x}$ (\$/kg)	$\mathrm{SO_2}$ (\$/kg)	PM (\$/kg)
BJ	1.61	1.61	1.61
TJ	1.37	1.02	1.02
HB	0.41	0.41	0.41
IM	0.2	0.2	0.2

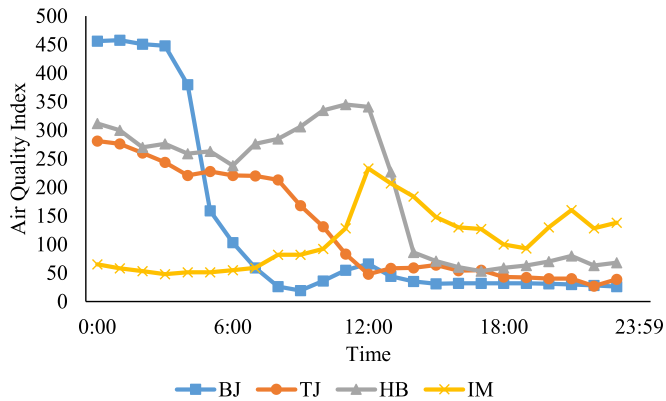

Fig. 7. AQI on January 16, 2015.

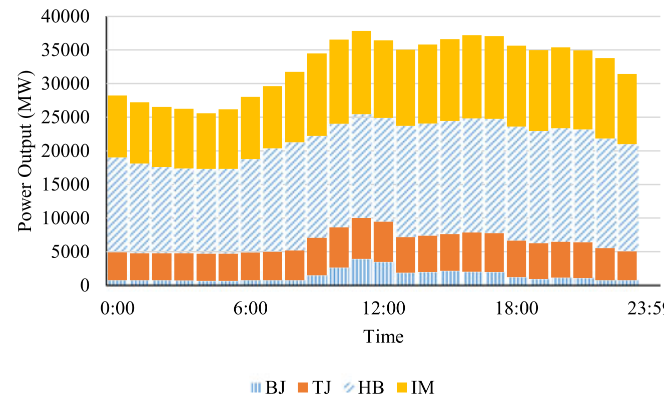

Fig. 8. Power output under EnPGS.

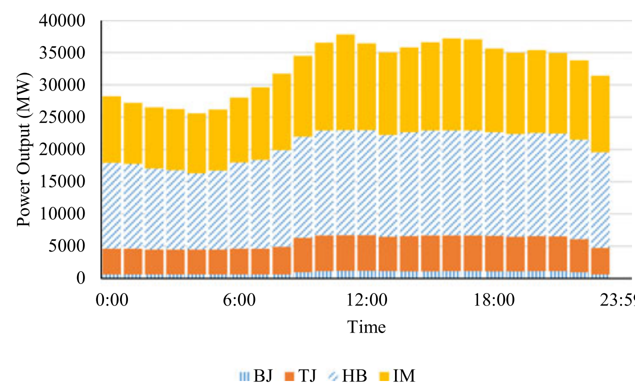

Fig. 9. Power output under EcPGS.

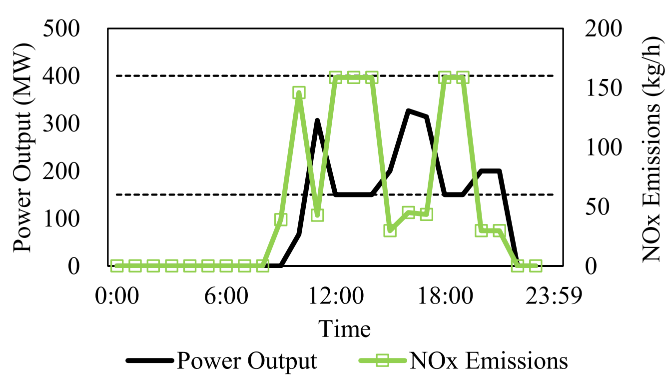

Fig. 10. Power output and NO_x emissions of CCGT #9.

TABLE V
COMPARISON OF ECPGS AND ENPGS ON DAILY EMISSIONS

Mode	NO_x Emissions	SO_2 Emissions	PM Emissions
EnPGS	406	757	428
EcPGS	495	1,202	443

Emissions in ton.

The tiered emission penalties are set according to the actual Chinese policy, which are given in Tables III and IV.

The actual AQI [31] on January 16, 2015 is used to test the EnPGS. Fig. 7 shows the AQI for the four regions with a 1-h resolution.

The tested model contains 119,148 constraints, 106,402 continuous variables and 15,700 binary variables. We use GAMS to solve the problem on a computer with dual Intel i5 cores and 8G RAM.

B. Results

Table V compares the daily emissions achieved using the proposed EnPGS model with those that would result from a traditional economic power generation scheduling (EcPGS). The EcPGS model is a security constrained unit commitment model [28], [29], whose objective is solely to minimize power generation costs (including the variable cost and startup and shutdown cost, excluding the emission penalties), as shown in (24). Model EcPGS does not consider regional emission constraints, while other constraints and parameters are the same with those in model EnPGS. Air pollution control technologies are also considered in the EcPGS model to calculate emissions.

$$\min z_2 = \sum_{u=1}^{N_u} \sum_{t=1}^{N_t} F_{u,t} + \sum_{u=1}^{N_u} \sum_{t=1}^{N_t} \left(p_u^{Y+} Y_{u,t}^{+} + p_u^{Y-} Y_{u,t}^{-}\right) \tag{24}$$

For this case study, the EnPGS reduces the emissions by 18% for NO_x, 37% for SO_2, and 3% for PM.

Fig. 8 shows the power produced in the 4 areas when optimized by the EnPGS, while Fig. 9 shows the same results as calculated by the EcPGS. The EcPGS does not commit the CCGTs in BJ because of their high cost. However, many CCGTs in BJ are turned on by the EnPGS on that day because the AQI is improving in BJ but getting worse in IM. The bad air quality in IM in the afternoon makes the emissions in IM tightly constrained, resulting in a reduction in the local power production of approximately 2,000 MW. The power outputs of BJ, TJ and HB increase at noon due to the changes in their regional AQI and the reduced power production in IM. The power that EcPGS would have produced in IM is first transferred to BJ, then to TJ and finally to HB. The power flows from HB to other regions change along with the power outputs of BJ, TJ and IM.

Fig. 10 shows the power output and NO_x emissions of a specific CCGT unit, to illustrate its emissions. This generator

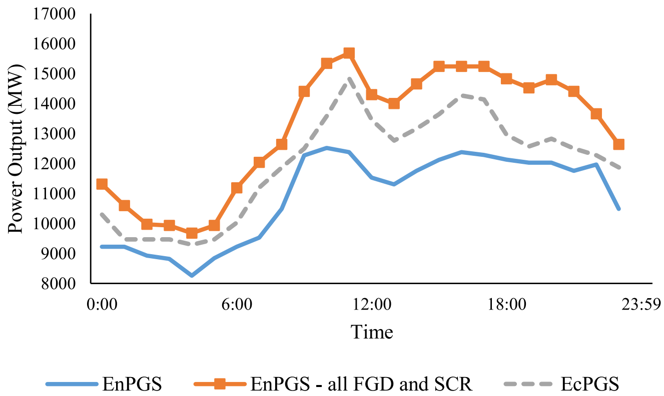

Fig. 11. Generation curves of IM.

TABLE VI
AIR QUALITY IN EACH SCENARIO

Date	BJ	TJ	HB	IM
2015/01/16	Unhealthy	Unhealthy	Unhealthy	Unhealthy for sensitive groups
2015/03/06	Very unhealthy	Unhealthy	Unhealthy for sensitive groups	Good
2015/03/09	Good	Good	Moderate	Good

is located in BJ, and is equipped with both LNB and SCR. The thin dashed lines indicate its maximum and minimum generation levels. The NO_x emissions during startup are 185 kg, accounting for 15% of its daily NO_x emissions, and are thus not negligible. Since its power output is lower than 50% of its 400 MW rated capacity during some periods, the SCR device must be shut down, resulting in significant NO_x emissions. The additional NO_x emissions resulting from this deactivation are about 676 kg, or 56% of the daily emissions.

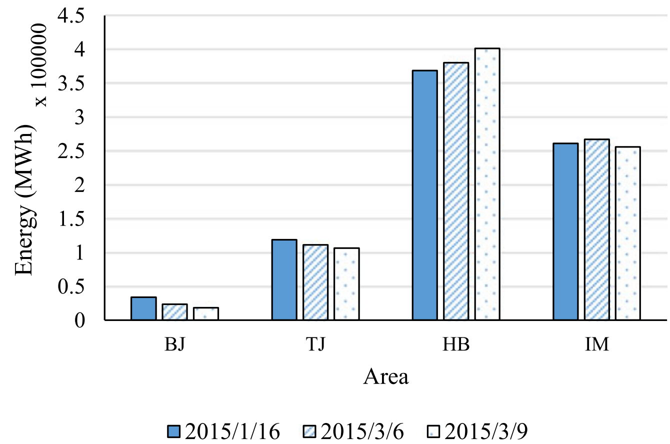

Fig. 12. Area energy output in each scenario.

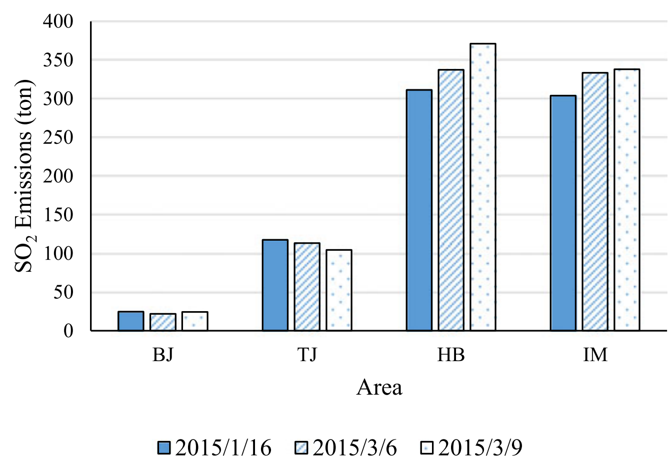

Fig. 13. Area SO_2 emissions in each scenario.

C. Sensitivity Analysis

1) Air Pollution Control Technologies: As provided in Table I, about 40% of the generators in IM are equipped with SCR, and 60% are equipped with FGD. If all the generators in IM were equipped with SCR and FGD, the local energy produced in IM on Jan. 16, 2015 would be 21% higher, while the emissions for the whole system would be reduced by 6% for SO_2 and 29% for NO_x. Fig. 11 shows a comparison of the generation profiles of IM.

2) Weather Effects: Two additional days were studied to analyze the effect of the weather and air quality on power system operation. Table VI provides the air quality [31] of the four areas for each day. Other conditions, including the load, have the same values as in the previous case.

Figs. 12 and 13 show the energy produced and the resulting emissions in each region for each of these days and illustrate the significant impact that weather has on generation scheduling. On March 6, weather in IM is relatively better and more energy is transmitted from IM to BJ/TJ/HB than on January 16. On March 9, the weather conditions are good in all regions, and the emission constraints can be relaxed. In this case, some relatively cheaper generators in HB increase their power outputs, while a few small generators with relatively high marginal costs in IM reduce their power outputs. Results show that additional generation capacity of 1,260 MW in IM is turned off on March 9 compared with that on March 6, because of the changes in weather conditions.

D. Case on Other Dates

To better test the effectiveness of the proposed EnPGS model, three more days with different AQIs and loads have been analyzed.

Fig. 14 compares the SO_2 emissions under EnPGS and EcPGS. EnPGS reduces the SO_2 emissions by 30–37% compared with EcPGS depending on the season. Fig. 15 shows that NO_x emissions are reduced by 14–18%. These results show that the reductions in emissions that the EnPGS achieves vary slightly on different days, but that it is suitable and effective in all the tested cases.

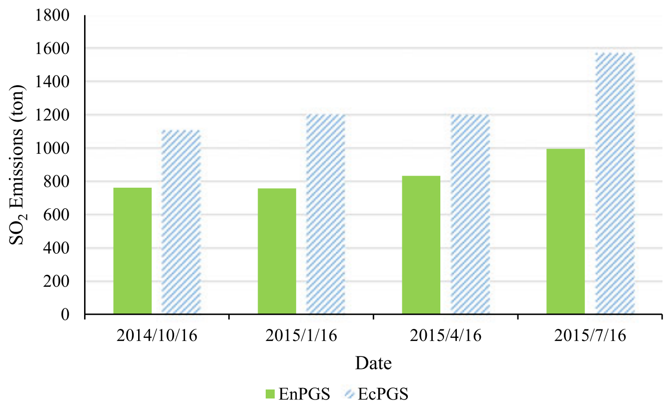

Fig. 14. SO_2 emissions by EnPGS and EcPGS.

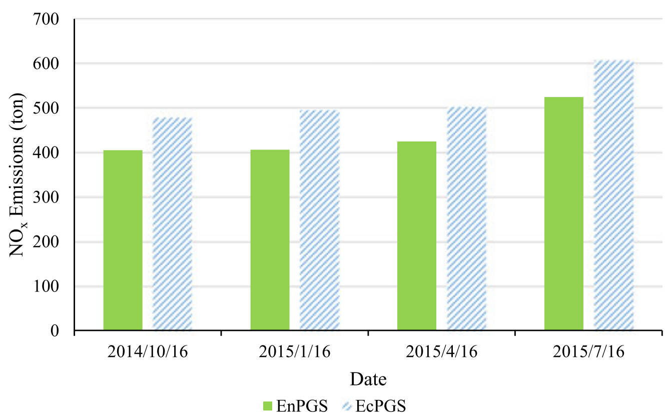

Fig. 15. NO_x emissions by EnPGS and EcPGS.

V. Conclusion

This paper focuses on the EnPGS problems. It first formulates the emission characteristics of NO_x, SO_2, and PM during normal operation as well as during startup and shutdown processes for coal- and gas-fired generating units that are or are not equipped with a variety of air pollution control technologies. Special characteristics such as the deactivation of SCR at low output and the burn mode switching of CCGTs are considered. It then proposes an EnPGS model, which takes into account weather-dependent regional emission constraints based on the forecasted AQI. It also considers tiered emission penalty rates for each generator. A case study suggests that the proposed EnPGS model could reduce emissions compared with a conventional economic dispatch model. The specific improvements in emissions vary from day to day. Generation schedules and corresponding emissions are significantly affected by the equipment and operation of air pollution control technologies as well as the weather conditions. These results suggest that the proposed model could be applied in control centers to balance economic and environmental objectives, using the AQI as currently defined or alternative indices that reflects the diffusion of pollutants to set the emission control targets. This paper considers local emission limits in each area. Future work could be extended to consider the transfer effects of pollutants among areas, and the corresponding impacts on generation scheduling.

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