Market-Based Electric Power Generation Planning with Emission Control

Shantha Daniel
Iowa State University

K. Jo Min
Iowa State University, jomin@iastate.edu

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Keywords
Generation planning, Strategic and tactical model co-ordination, emission control

Disciplines
Natural Resource Economics | Oil, Gas, and Energy | Operational Research

Comments
Market-Based Electric Power Generation Planning with Emission Control
Shantha Daniel and K. Jo Min, Department of Industrial and Manufacturing Systems Engineering, Iowa State University, Ames, Iowa 50011. USA

Abstract

Recently, there has been an increasing emphasis on environmental concerns in the electric power industry, especially air pollution. Under this circumstance, we formulate a generation planning model that considers not only the conventional production costs, but also the costs related to air pollution. In particular, we will focus on sulfur dioxide emission which is heavily regulated by Environmental Protection Agency via emission permits. For this particular type of pollutant, we present a generation planning model consisting of an annual strategic model and a weekly tactical model. An illustrative numerical example is provided.

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1. Introduction

The optimal generation planning of an electric utility is a complex problem due to the presence of various physical, economical and temporal constraints associated with it. Generation planning decisions have traditionally been classified as long-term, short-term and real-time decisions. Long-term decisions refer to decisions related to one to a few years of operation, while short-term decisions deal with weekly operations and real-time decisions are those of daily to hourly operation.

In recent times, generation planning has been further complicated by compliance with various emission regulation programs. The sulfur dioxide emissions from all thermal units are regulated by the Environmental Protection Agency (EPA) via the Acid Rain Program (ARP). Under the ARP, regulated utilities should own enough allowances, also known as permits, to cover their annual emissions. An allowance gives the owner (utility) with the right to emit one ton of sulfur dioxide [1]. Utilities are provided with an initial annual allocation by the EPA and they can buy additional allowances in the permits market. In this paper we model the strategic and tactical generation planning of an electric utility with multiple thermal generation units.

The problem of market based generation planning with explicit consideration of emission control costs is very relevant due to the drastic increase in allowance prices, improved emission control technology and the rising demand for reliable, clean and cheap electricity. In this paper we study the generation planning of an electric utility at two different time points – the strategic annual planning and the tactical weekly planning. The need to study generation planning at these two levels stems from the fact that sulfur dioxide emission compliance and planned maintenance schedules have an annual time horizon while various other generation decisions such as unit commitment and load satisfaction, have a weekly time line.

The coordinated simulation based study of two models, a long-term model and a short term model, for optimal sulfur dioxide emission compliance was done by Manetsch [2] and Breipohl et al [3]. Other models that have suggested coordination between long-term and short term models were analytical models by Gardner et al [4] with focus on the fuel allocation and scheduling difficulty and not the emission control problem. In [4], the various co-ordination mechanisms are discussed. The paper details various primal methods of setting physical constraints on the optimization of the short term model based on the optimal result of the long-term model. It also provides a discussion on the dual method of providing price signals from the long-term model to the short term model. More recently, the various co-ordination mechanisms between long-term and short-term operational planning models in electricity markets was compared by Reneses et al [5]. Marwali et al [6] have studied the coordinated generation scheduling with network constraints but they do not consider the explicit emission control cost in the form of scrubbing cost and cost of buying allowances to cover emissions in excess of annual allocation.
In our paper, we use the primal approach of setting availability times for the generation units in the weekly model based on an annual maintenance schedule. We also provide weekly emission targets based on the total annual emissions from the annual model. In the weekly model, the unit commitment decisions are done based on these availability times obtained from the primal maintenance constraints and the emission limits. The paper is organized as follows, in section 2 and section 3 we provide an outline of the strategic annual model and the tactical weekly model along with the co-ordination aspects between these models. A simple numerical example is provided in section 4 followed by conclusion in section 5.

2. Strategic Annual Model

The electric utility has $i$ generation units of varying generation capacities and emission rates. Each of these $i$ units have a scrubber module or de-sulfurization module attached to them for sulfur dioxide emission control. It is assumed that the utility is a monopoly in the electricity market and a price taker in the permits market. It is also assumed that the utility is a chronically polluting firm which only buys allowance after its annual EPA allocation is exhausted. The annual strategic model is a profit maximizing model that provides the utility with an annual generation plan including scrubber operation, weekly emission limits and the annual maintenance schedule. The various notations used in the model and the definition are given below. The annual model variables are represented by upper case letters while lower case letters are used to represent the decision variables in the weekly model.

2.1 Notations

$P_t^E (X_{it})$: Price of electricity as obtained from the Inverse demand function of week $t$. ($/MWh$)
$C_t^p (X_{it})$: Cost of operating generation unit $i$ at the power level $X_{it}$ MW for one hour in week $t$. ($/hr$)
$K_i$: Co-efficient of the power production function used to calculate operation cost;
$A_i$: Scalar exponent value used in the power production function.
$C_i^{E^i}$: Cost of scrubbing sulfur dioxide from unit $i$’s emissions. ($/lbs$)
$C_i^{M^i}$: Cost of planned maintenance activities on unit $i$. ($)$
$P^A$: Price of allowance ($$/ton$)
$E_i$: Emission rate of unit $i$ (lbs/MWh)
$Cap_i$: Maximum generation capacity of unit $i$ (MW)
$a_i$: Removal percentage of scrubber attached to unit $i$. $a_i \in (0, 1)$
$O_i$: Maximum number of weeks unit $i$ can remain without maintenance (weeks)
$A_i$: Annual EPA allocation of allowance to unit $i$. (tons)
$B_t$: Number of hours in week $t$ (hours)
$X_{it}$: Power level of unit $i$ for each hour in week $t$ (MW)
$Y_{it}$: Amount of sulfur dioxide removed from unit $i$’s emissions in each hour of week $t$ by scrubbing. (lbs/hr)
$Z_{it}$: Amount of sulfur dioxide emitted into the atmosphere from unit $i$ in each hour of week $t$ (lbs/hr)
$M_{it}$: Decision to conduct maintenance on unit $i$ in week $t$. Binary variable with $M_{it}$ equal to 0, when unit is offline for maintenance and 1 otherwise.
$I_i$: Binary variable with $I_i$ equal to 0 when $A_i > Z_{it}$ and 1 if $A_i < Z_{it}$. Decision to buy allowances in a year for unit $i$.

2.2 Model

The annual model is given below,

$$\text{Max} \left( \sum_i B_i \left[ P_t^E \left( \sum_t X_{it} \right) X_{it} - \sum_t C_t^p (X_{it}) + C_i^E Y_{it} + C_i^M (1 - M_{it}) \right] - \frac{P^{A}}{2240} \left[ I_i \left( \sum_t 2240 A_i - \sum_t Z_{it} \right) \right] \right)$$  \hspace{1cm} (1)

s.t

$$X_{it} \leq \text{Cap}_i M_{it} \quad \forall i,t;$$  \hspace{1cm} (2)

$$Y_{it} \leq a_i E_i X_{it} \quad \forall i,t;$$  \hspace{1cm} (3)
The first term of equation (1) represents the annual revenue obtained by the sale of electricity. The revenue is obtained by using the forecasted inverse demand function for week $t$. The second term in the objective function represents the cost of producing power from each of the $i$ units for each hour of week $t$ when each unit is being operated at $X_{it}$ MW. For computing the cost of power production we use the commonly used power production function of $K_i(X_{it})^{\alpha_i}$. The third term in equation (1) represents the scrubbing cost associated with unit $i$ in week $t$. Here the cost of scrubbing is assumed to be linearly dependent on the quantity of sulfur dioxide removed from unit $i$’s emissions. The fourth term represents the maintenance cost of unit $i$ in week $t$. The maintenance cost will be $C_i$ when the unit is on maintenance and 0 at other times. It is assumed that the time it takes to maintain all units will be the same. The last term in the objective function refers to the cost of buying permits to cover emissions that are in excess of the unit’s annual allocation.

The first constraint states the power level of each unit at every point should be less than or equal to the maximum capacity of the unit. The second constraint sets a maximum limits to the amount of sulfur dioxide that can be removed from the units emissions in one hour of each week $t$. This is a function of the emission rate $E_i$ and the maximum removal percentage, $a_i$, of the scrubber attached to the unit. The third constraint determines the amount of sulfur dioxide emitted into the atmosphere by each unit in the whole year. The fourth constraint states that the maximum number of weeks that a unit can be operated without maintenance is limited. The fifth constraint specifies the maintenance decision while the sixth constraint states that allowances will be bought only when the amount of emissions is greater than the annual EPA allowance allocation. The last constraint is the non-negativity constraint of the decision variables.

### 3. Tactical Weekly Model

The tactical weekly model determines the unit commitment decision for a week based on the more recent weekly load forecast. The weekly model also has explicit consideration of unserved energy. Unserved energy is defined as the amount of energy by which the load faced by the system exceeds the available generation capacity. The additional notations for the weekly model is provided below.

#### 3.1 Notations

- $C_i^p(x_{ih})$: Cost of operating generation unit $i$ at the power level $x_{ih}$ MW during hour $h$ in week $t$. ($$/hr)$
- $C_i^{US}$: Unserved Energy cost at hour $h$ of week $t$. ($$/MWh)$. Assumed to be a constant.
- $x_{ih}$: Power level of unit $i$ during hour $h$ in week $t$ (MW)
- $y_{ih}$: Amount of sulfur dioxide removed from unit $i$’s emissions in hour $h$ of week $t$ by scrubbing. (lbs/hr)
- $z_{ih}$: Amount of sulfur dioxide emitted into the atmosphere from unit $i$ in each hour of week $t$ (lbs/hr)
- $UC_i$: Decision to commit unit $i$ for a week. Binary variable with $UC_i$ equal to 0, when unit is not committed and 1 when committed.
- $Z_{it}$: Amount of sulfur dioxide emitted into the atmosphere from unit $i$ in each hour of week $t$ (lbs/hr) (From annual model optimization)
- $L_{ih}$: The load faced by the system in hour $h$ of week $t$ (MW)

It is to be noted that the subscript of week $t$ is left out in the notations. This is because the weekly model is run every week with new weekly updated forecasts.
3.2 Model

The weekly cost-minimization problem is given below.

\[
\text{Min} \left\{ \left( \sum_t \left( C^P_i \left( x_{ih} \right) + C^E_i \left( y_{ih} \right) \right) \right) \left( \sum_t \left( x_{ih} U_{Ci} \right) \right) + C^\text{US}_h \left( L_{ih} - \sum_t x_{ih} \left( U_{Ci} \right) \right) \right\} \) \ (9)
\]

s.t

\[
x_{ih} U_{Ci} \leq \text{Cap}_i \quad \forall \ i, h \text{ in every } t; \quad \text{(10)}
\]

\[
y_{ih} \leq \alpha_i E_{ih} \quad \forall \ i, h \text{ in every } t; \quad \text{(11)}
\]

\[
z_{ih} = E_{ih} x_{ih} - y_{ih} \quad \forall \ i, h \text{ in every } t; \quad \text{(12)}
\]

\[
U_{Ci} \leq M_{hi} \quad \forall \ i \text{ in every } t; \quad \text{(13)}
\]

\[
\sum_{h} \sum z_{ih} \leq Z_{it} \quad \forall \ t; \quad \text{(14)}
\]

The objective function of the model in equation (9) consists of four cost terms - the power production cost term, the scrubbing cost term, the unserved energy cost and the maintenance cost. The first three costs come into picture only when the units are committed. While the last term comes into picture only when the units are not committed and out on maintenance. The first constraint given by equation (10) is the capacity constraint associated with all the committed units. The second constraint is similar to equation (3) and states the maximum amount of sulfur dioxide that can be removed in each hour by scrubbing. The third constraint determines the amount of sulfur dioxide emitted into the atmosphere. The fourth and fifth constraints are the coordination points between the annual model and the weekly model. The fourth constraint stipulates that a unit on maintenance cannot be committed and the fifth constraint sets an upper limit on the weekly emissions based on the emissions in that week obtained from the annual model.

The annual strategic model is run once at the beginning of the year to determine the optimal annual planned maintenance schedule \((M_{it})\), the generation planning \((X_{it})\), operation of the scrubbers \((Y_{it})\) and the total annual emissions \((Z_{it})\). Among the outputs of the annual model, the annual planned maintenance schedule \((M_{it})\) and the total annual emissions \((Z_{it})\) are used as constraints in the weekly planning model. The weekly tactical model is run at the beginning of each week to determine unit commitment decisions \((U_{Ci})\), hourly power level of the unit \((x_{ih})\) and hourly scrubber operation \((y_{ih})\) and the hourly emissions \((z_{ih})\) of each week. The annual strategic model and the weekly tactical model are linked by two points - the availability time determined by the annual maintenance schedule and the weekly emission limits based on the total optimal annual emissions. These co-ordination points are enforced in the tactical model by equations (13) and (14). Equation (13) ensures that units that are out on planned maintenance as per the optimal annual planned maintenance schedule are not committed for that week. Equation (14) ensures that the total weekly emissions that are obtained by each week’s generation planning does not exceed the optimal weekly emission limits obtained from the annual model. The chronological order of events and the linkages are depicted in Figure 1.

Figure 1: Flowchart of Long-term and Short-term Generation Planning.
The use of two models is justified due to the fact that while the annual generation planning is conducted the utility will have only an annual load forecast. The fact that real-time load faced by electric utilities vary widely from the forecasts is well known. This is reflected on the various generation planning models in the unserved energy term being a part of their objective function. In our paper we address this issue by having two models one of which will be based on more accurate load forecasts. There are different methods by which the long-term and short-term models can be co-coordinated. In [5] three common co-ordination methods are illustrated – the primal method, the dual method and the marginal valuation method. In the primal method physical constraints are set on the short-term use of resources based on the long-term model results. In the dual method the marginal value of the resources in the long-term time horizon is incorporated into the short-term model. In marginal valuation method, a continuous valuation of the resources is obtained for a range of operating conditions the utility might face. In this paper, we use the primal method of co-ordination for its ease of use and as a starting point. The coordination mechanism of setting hard physical (primal) constraints on emissions in a week has its drawback. This might force the weekly model to behave in a suboptimal way, by limiting the production in each week and hence incurring unserved energy costs [5].

4. Numerical Example
A simple numerical example to illustrate the model, the details of which are provided in this section, was done using the LINGO.9 software (student version). Due to the large number variables involved in the problem, the numerical example is more illustrative than insightful. It is noted that the values used in the numerical example are not representative of real-world situations. The example is a 2 unit, 3 week strategic model with 15hrs in each week. The inverse demand function for the year was assumed constant for every week of the year and given by $80-0.2X_{it}$. The price of allowance was taken as $950$/ton (950/2240 ($/lbs)) and the emission rates of the two units were 16.35 and 28.35 (lbs/MWh) respectively. Unit 1 had a maximum capacity of 150 MW while Unit 2 had a maximum capacity of 250 MW and annual EPA allocation of 1500 tons and 2500 tons respectively. The output of the annual model’s numerical example is given below in Table 1.

<table>
<thead>
<tr>
<th>Week</th>
<th>X_{it}</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit</td>
<td>1</td>
<td>0</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>250</td>
<td>250</td>
<td>250</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Week</th>
<th>Y_{it}</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit</td>
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<td>0</td>
<td>2207.25</td>
<td>2207.25</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>6733.125</td>
<td>6733.125</td>
<td>6733.125</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Week</th>
<th>M_{it}</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Week</th>
<th>Z_{it}</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit</td>
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<td>0</td>
<td>6131.250</td>
<td>6131.250</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>8859.375</td>
<td>8859.375</td>
<td>8859.375</td>
</tr>
</tbody>
</table>

Table 1: Numerical Example Output for Annual Model

Based on these outputs, the weekly tactical model was run for one representative week. The hourly load was obtained by using the random number generator in MS Excel. The unit commitment decision variable was decided based on the $M_{it}$'s of the annual model output and the weekly generation was dependent on the weekly emission targets obtained from the annual model. Week one was chosen as the representative week. It was observed that in accordance with $M_{11}$ being 0 that all the $x_{1h}$'s and $y_{1h}$'s were zero. Since $M_{21}$ was 1, unit 2 was committed and it was observed that the weekly emission limit of $Z_{21}$ was a binding one. It was also observed that to ensure that the emission limit is not exceeded, the production is less that the hourly load in hours which have less demand and hence will have less unserved energy cost. The numerical example illustrated how the annual generation planning influenced the weekly generation planning.
5. Conclusions and Future Research

In this paper we have formulated the annual strategic and weekly tactical model of market based generation planning. The sulfur dioxide emission compliance was considered explicitly in the form of compliance costs. The compliance costs arise from the participation of the utility in the permits market and due to its emission control technique of scrubbing its unit’s emissions. The utility participates in the permits market if its annual emissions that are in excess of each of its unit’s annual EPA allowance allocation and it buys allowances from the permits market to cover.

In addition, we also formulate the generation planning model in a coordinated manner with an annual model that sets the annual maintenance schedule and weekly emission limits and a weekly tactical model that uses these primal constraints in the weekly generation planning with more recent forecasts of load. The advantage of having these two models is that the utility has the flexibility to make weekly generation planning decisions such as unit commitment decisions based on recent load forecasts while still satisfying sulfur dioxide emission control compliance constraints that are yearly in nature. This provides the opportunity to the planner to fulfill each constraint on generation planning at a point in the time horizon that is more appropriate to the constraint.

The drawback of having fixed emission limits that are based on an annual forecast is that the emissions and subsequently the production of power cannot adjust to sudden load fluctuations. In addition while the updation of the weekly model based on the annual model is facilitated, the current models do not address the update of the annual model based on the weekly model. It is also noted that the problem size and the rate at which the size increases might make the problem intractable and computationally expensive. These issues will be addressed in future by establishing an analytical link that updates the annual model based on the results of the weekly model. Also a solution procedure that will make better use of the underlying structure of the problem will be identified and implemented. An algorithm that will run the annual and weekly models till an optimal generation planning for the year with explicit consideration of emission control costs will be formulated and implemented in future.

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1. Clean Air Markets- Programs and Regulations, EPA webpage with information about the Acid Rain Program. Accessed on 1/31/06 at http://www.epa.gov/airmarkets/arp/overview.html