Maintenance Strategies for a Generation Company in a CO_2 Allowance Market Environment

Wei Sun, *Member, IEEE*, and Qun Zhou, *Member, IEEE*

Abstract--**In a competitive market environment, generation companies (GenCos) can schedule the maintenance periods to maximize their profits. Independent System Operator's (ISO) functionality is also considered from the view point of system reliability and cost minimization. Carbon Dioxide (CO_2) mitigation policies, such as CO_2 emission cap-and-trade, help to reduce consumption in fossil energy and promote a shift to renewable energy resources. Considering these new effects, GenCos need to adjust their scheduling strategies in the electricity market and bidding strategies in CO_2 allowance market. In this paper, the emission-constrained generation scheduling problem (GSP) involving generation maintenance scheduling and CO_2 emission cap-and-trade is formulated as a Mixed Integer Bi-Level Linear Programming (MIBLP) problem. A novel solution methodology is proposed, and simulation results based on the PJM 5-bus system test case demonstrate that the proposed MIBLP-based model is able to provide valuable information for GenCos' decision making in both electricity and CO_2 allowance markets.**

Index Terms—**CO_2 allowance, cap-and-trade, generation maintenance scheduling, mixed integer bi-level linear programming**

I. INTRODUCTION

GENERATION scheduling in a restructured industry environment is a critical task to maintain the stability and security of power systems and efficient operation of electricity markets. Traditional GSPs involve a number of objectives. They are real-time security analysis, short-time generation operation, i.e., security-constrained unit commitment (SCUC) and security-constrained optimal power flow (SCOPF), mid-term generation operation planning, i.e., maintenance scheduling, fuel allocation, emission allowance, optimal operation cost, and long-term generation resource planning [1]. However, different GSPs are emerging under a new environment, i.e., generation operation planning considering CO_2 emission regulation. CO_2 emission regulation affects both short-term generation operation and mid-term generation operation planning. GSP considering CO_2 emission regulation is to investigate the effects of this new mechanism on current system operation and the corresponding adjustment of GenCos' decision making.

Emission trading is an efficient market-based mechanism to regulate CO_2 emission. CO_2 emission cap-and-trade helps to reduce consumption in fossil energy and promote a shift to renewable energy resources. In the U.S., Regional Greenhouse Gas Initiative (RGGI) operates the first mandatory cap-and-trade program to cap regional power plants' CO_2 emissions. The cap will be 10 percent lower by 2018 than it is at the start of the RGGI program in 2009 [2]. Recently, California cap-and-trade program was approved by the Air Resources Board to build a carbon market starting in 2013 to cut carbon emissions.

The regulation of CO_2 emissions from electric power industry to mitigate global warming brings a new challenge to GenCos. In the competitive market environment, GenCos schedule the maintenance periods to maximize their profits and also consider ISO's functionality from the view point of system reliability [3]. Taking into account the effects of CO_2 emission regulation, GenCos need to adjust their strategies in electricity market and bidding strategies in CO_2 allowance market. Hence, an appropriate model of GSP considering CO_2 emission cap-and-trade needs to be developed.

There have been various research projects about the effects of emission constraints on electric power systems. Reference [4] includes emission constraints in economic dispatch (ED) by a weights estimation technique to solve environmentally constrained economic dispatch problem. The work of [5] provides a set of dispatching algorithms to solve the constrained emission dispatch problem with SO_2 and NO_x emission constraints. References [6] present a short-term unit commitment approach based on Lagrangian Relaxation technique to solve the emission constrained unit commitment problem. However, these models are developed to solve SO_2 or NO_x emission regulation problem and do not apply to the CO_2 emission regulation without detailed modeling of a CO_2 allowance market. References [7] formulate the electric power and NO_x allowances market as complementarity problems by using Cournot game. In [8], a nonlinear complementarity model is used to investigate long-run equilibrium of alternative CO_2 emissions allowance allocation systems in an electricity market. However, the daily electricity market and quarterly CO_2 allowance auction market should be incorporated in an appropriate time framework.

In this research, the CO_2 allowance market is formulated by the Cournot equilibrium model. Practical market rules, such as those in RGGI, are considered in the proposed model. Then the emission-constrained GSP involving generation maintenance scheduling and CO_2 allowance cap-and-trade, in

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a three-year CO_2 allowance compliance period, is investigated. By utilizing the developed CO_2 allowance market model, this new GSP problem is formulated as a MIBLP problem. Based on Benders decomposition, a novel solution methodology is developed to solve this combinatorial optimization problem. The proposed transformation procedure and decomposition method lead to an optimal and efficient solution to this large-scale complex optimization problem.

Simulation results based on the PJM 5-bus system test case demonstrate that the proposed MIBLP-based model is able to provide information of electricity price and scheduled generation commitment and dispatch for GenCos to make decisions in both the electricity market and CO_2 allowance market. With the valuable information, GenCos are able to determine their optimal mid-term operation planning and short-time operation schedules participating in both markets. To the best of the authors' knowledge, this problem has not been solved.

II. CO_2 ALLOWANCE MARKET MODEL

The CO_2 emission allowance market is formulated as a Cournot equilibrium model based on the market rules in RGGI. In RGGI, the primary market offer initial allowances through a single-round, uniform-price, and sealed-bid auction. The price paid by all bidders is equal to the highest rejected bid. The characteristics of allowance banking, auction limit, CO_2 reserve price, offset limit, etc. are considered in the developed model.

Cournot competition models an industry structure in which companies compete for the amount they produce, which they decide independently and at the same time. Each GenCo has its own demand function of CO_2 allowances. Therefore, bidding price is a parameter and the bidding amount is a decision variable.

During each auction t_q, first, each GenCo submits its bidding offer (λ_{it}, q_{it}) to the CO_2 allowance market, where λ_{it} and q_{it} are the bidding price and amount of firm i during t_q. By solving the following optimization problem, each GenCo decides its bidding strategy:

$$\begin{aligned}
\max_{P_{it},q_{it},OS_{it}} \quad & \sum_t \left(\lambda_{it}^e g_{it} - C_{it}^p - \lambda_t^{co_2} A_{it} - C_{it}^{os} OS_{it}\right) \\
s.t. \quad & \sum_t k_i g_{it} \le \sum_t \left(A_{it} + OS_{it}\right) \\
& \sum_t OS_{it} \le \sum_t 0.033 k_i g_{it} \\
& u_{it} G_i^{\min} \le g_{it} \le u_{it} G_i^{\max}, \quad \forall t \\
& \forall g_{it}, q_{it}, u_{it}, OS_{it} \ge 0, \quad t \in \{t_d\}
\end{aligned} \tag{1}$$

where, λ_{it}^e is Locational Marginal Price (LMP) at node i of time t, g_{it} is power output of generator i of time t, C_{it}^p is marginal production cost function of generator i of time t, $\lambda_t^{co_2}$ is the CO_2 allowance price for auction time t, A_{it} is the allowance dispatch for firm i of time t, C_{it}^{os} is offset cost of firm i of time t, OS_{it} is offset used by firm i of time t, k_i is CO_2 emission rate of generator i, u_{it} is binary variable of the commitment of generator i of time t, $G_i^{\max} / G_i^{\min}$ is maximum/minimum generation output limit of generator i, and t_d represents time period of each day. Based on [9], production cost function can be approximated by piecewise linear function, then it can be rewritten as:

$$C_{it}^p = u_{it}\left[a_i + b_i G_i^{MIN} + c_i\left(G_i^{MIN}\right)^2\right] + \sum_{j=1}^{k} S_{ij}\delta_{ijt}, t \in \{t_d\} \tag{2}$$

where, (a_i, b_i, c_i) are coefficients of production cost function, S_{ij} is slope of block j of the piecewise linear production cost function of unit i, and δ_{ijt} are power produced in block j of the piecewise linear production cost function of unit i in period t.

Decision variables satisfy the following constraints:

$$\begin{aligned}
& g_{it} = u_{it} G_i^{MIN} + \sum_{j=1}^{k} \delta_{ijt}, \quad t \in \{t_d\} \\
& \delta_{i1t} \le G_{i1} - G_i^{MIN}, \quad t \in \{t_d\} \\
& \delta_{ijt} \le G_{ij} - G_{i(j-1)}, \quad t \in \{t_d\} \\
& \delta_{ikt} \le G_i^{MAX} - G_{i(k-1)}, \quad t \in \{t_d\} \\
& \delta_{ijt} \ge 0, \quad j = 1,\ldots,k \quad t \in \{t_d\}
\end{aligned} \tag{3}$$

where, G_{ij} is upper limit of block j of the piecewise linear production cost function of unit i.

The objective is to maximize the profit, which is the revenue from selling power to electricity market minus the costs of generation, buying allowances from CO_2 market and using offsets. The first constraint requires each GenCo to have sufficient allowances to cover its generated CO_2 during t_q. The second constraint requires that the use of CO_2 offset allowances is constrained to 3.3% of a unit's total compliance obligation during t_q. (Offsets referred to the project-based emissions reductions outside the capped sector.) The third constraint is the generation output limit, and all decision variables should be non-negative.

After the market clearance, for each auction t=t_q, $\lambda_t^{co_2}$ and A_{it} are obtained by solving the following market clearing optimization problem:

$$\begin{aligned}
\max_{A_{it}} \quad & \sum_i \left(\lambda_{it} A_{it}\right) \\
s.t. \quad & \sum_i A_{it} = CAP_t^{co_2}, \quad \left(\lambda_t^{co_2}\right) \\
& A_{it} \le 0.25 CAP_t^{co_2}, \quad \forall i \\
& 0 \le A_{it} \le q_{it}, \quad \forall i
\end{aligned} \tag{4}$$

where, $CAP_t^{co_2}$ is total amount of allowances in the auction of time t.

The first constraint is based on the assumption that all allowances will be sold to assure that there is one CO_2 allowance price. The second constraint is based on the auction rules in RGGI that it establishes a total limit for the number of allowances that entities may purchase in a single auction, equivalent to 25% of the allowance offered for sale in any single auction. The third constraint restricts that each GenCo's bought allowances should be nonnegative and should not exceed its bidding allowances.

Given (λ_{it}, q_{it}), the optimal solution ($A_{it}, \lambda_t^{co_2}$) of the concave optimization problem (4) can be obtained by solving its Karush-Kuhn-Tucker (KKT) conditions as following:

$$\begin{aligned} &\sum_i A_{it} - CAP_t^{co_2} = 0 \\ &0 \le A_{it} \perp -\lambda_{it} + \lambda_t^{co_2} + w_i^1 - w_i^2 \ge 0, && \forall i \\ &0 \le w_i^1 \perp q_{it} - A_{it} \ge 0, && \forall i \\ &0 \le w_i^2 \perp A_{it} \ge 0, && \forall i \\ &0 \le w_i^3 \perp 0.25CAP_t^{co_2} - A_{it} \ge 0, && \forall i \end{aligned} \tag{5}$$

where $\left(w_i^1, w_i^2, w_i^3\right)$ are slack variables to each inequality constraints in (4).

By adding KKT conditions (5) as constraints to each GenCo's maximization problem (1), each GenCo's optimization problem is formulated as the mathematical problem with equilibrium constraints (MPEC). Each GenCo solves the MPEC problem and all GenCos together may reach an equilibrium point of the equilibrium problem with equilibrium constraints (EPEC).

In the literature, there are several methods available to solve the EPEC problem such as, Diagonalization techniques (Gauss-Jacobi and Gauss-Seidel type methods), or sequential nonlinear complementarity problem (SNCP) approach. In this research, based the advanced technique developed in [10], the EPEC formulation is transformed to a nonlinear complemetarity problem (NCP) and nonlinear programming problem (NLP), which can be solved by AMPL/MINOS commercial solver. The detailed algorithm, solution methodology and numerical examples can be referred to [11].

III. NEW GENERATION SCHEDULING PROBLEM MODEL

Under the new emerging circumstance of CO$_2$ emission regulation, GenCos need to participate in both electricity market and CO$_2$ allowance market. They need to purchase enough allowances from CO$_2$ allowance market to cover emitted CO$_2$ from producing electricity, while at the same time, they bid to the electricity market. In order to maximize the profit, GenCos need to adjust and coordinate their strategies in both markets. An appropriate model is needed to analyze this new GSP, as shown in Fig. 1.

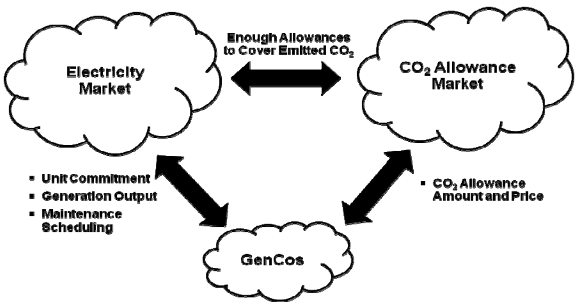

Fig. 1 New GSP in two markets

GenCos participate in electricity markets daily and they also auction in CO$_2$ allowance market quarterly. They need to know the amount and price of CO$_2$ allowances to make decisions about how to bid in electricity market, while they bid to CO$_2$ allowance market based on the information of electricity price and scheduled generation commitment and dispatch. The market environment for GenCos is illustrated in Fig. 2. Moreover, during the three-year CO$_2$ allowance compliance period, the coordination of midterm generation maintenance scheduling with short-term unit commitment has to be considered to maintain adequacy in midterm planning and security in short-term operation planning [1]. Therefore, in this three-year time framework, GSP involving generation maintenance scheduling, unit commitment and CO$_2$ allowance cap-and-trade need to be investigated. The time horizon of three-year GSP is shown in Fig. 3.

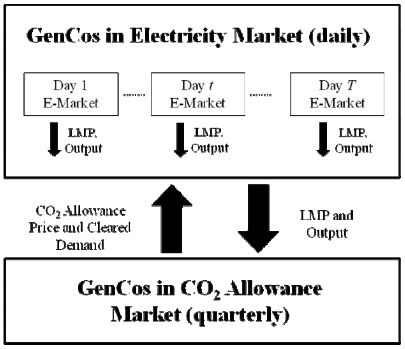

Fig. 2. GenCos' interactions in electricity and CO$_2$ allowance markets

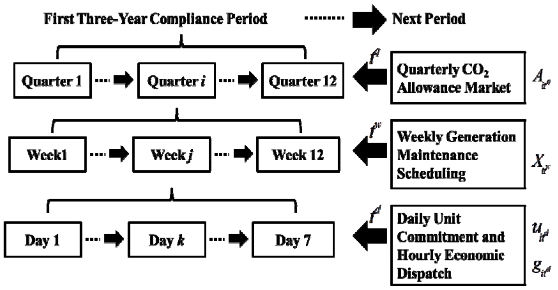

Fig. 3. Time horizon of three-year GSP

A. Problem Structure

GenCos' decision making will be based on the following optimization problem:

Max Total Profit during Time Period T
subject to
Generation Maintenance Scheduling Constraints
SCUC and SCOPF Constraints
CO$_2$ Allowance Market Constraints

By solving this optimization problem, GenCos are able to decide the following ***Decision Variables***: A_{it}, OS_{it}, $\lambda_t^{co_2}$, λ_{it}^e, g_{it}, u_{it} and x_i, which is the binary variable of the maintenance schedule of generation i in period t.

Then this new GSP is formulated as a bi-level optimization problem, as shown in Fig. 4. In the upper level problem, GenCos make decisions to maximize their own profit. And in the lower level problem, after receiving the bids from GenCos, ISO and CO$_2$ allowance market operator will clear both markets and make available the electricity price, generator commitment, generation dispatch level, CO$_2$ allowance price and cleared demand.

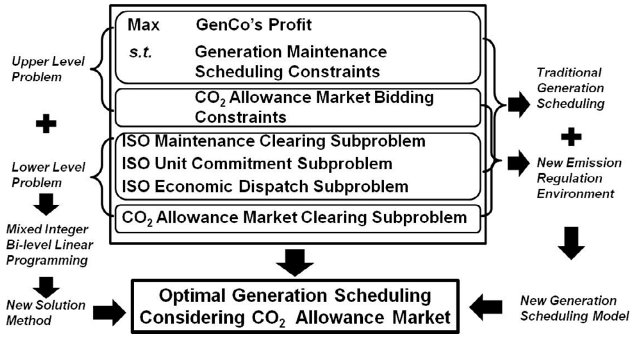

Fig. 4 Structure of new GSP

For profit-seeking GenCos, full consideration of both markets can provide detailed signals to guide their strategic behaviors. It provides the information of power flow, electricity price, and generation output level, etc., which significantly enhance the awareness of GenCos of the system condition and provide better support for their decision makings in two markets. This model is not intended to give precise prediction of electricity prices, but market traders may use the results as a reference to make the coordinated strategies. If simplifying the model using forecasted electricity price, the detailed interactions between two markets cannot be explored, then GenCos can only produce one-sided strategies.

B. Upper Level Optimization Problem Formulation

Objective Function: GenCo's profit is its revenue from selling power to the electricity market minus its cost of fuel production, startup, shutdown, maintenance and CO_2 allowance. GenCo *i* maximizes its profit by solving the following optimization problem (4).

$$\begin{aligned} \max_{g_{it},x_{it},q_{it},OS_{it}} \quad & \sum_{t\in\{t_d\}} \left\{ \lambda_{it}^{e} g_{it} - C_{it}^{p} - C_{it}^{su} - C_{it}^{sd} \right\} - \sum_{t\in\{t_w\}} C_{it}^{m} \\ & - \sum_{t\in\{t_q\}} \left\{ \lambda_{t}^{co_2} A_{it} + C_{it}^{os} OS_{it} \right\} \end{aligned} \tag{6}$$

Where, t_w represents time period of each week, ${C_{it}}^{su}/{C_{it}}^{sd}/{C_{it}}^{m}$ is start-up/shut-down/maintenance cost function of generator *i* of time *t*, and $SU_{it}/SD_i/MT_{it}$ is start-up/shut-down/maintenance cost of generator *i* of time *t*. The following Mixed Integer Linear Programming (MILP) formulation was proposed in [9]:

$$\left.\begin{aligned} C_{it}^{su} \ge SU_{ik}[u_{it} - \sum_{j=1}^{k} u_{i(t-j)}] \\ C_{it}^{su} \ge 0 \end{aligned}\right\}, \quad t\in\{t_d\} \tag{7}$$

$$\left.\begin{aligned} C_{it}^{sd} \ge SD_i[u_{i(t-1)} - u_{it}] \\ C_{it}^{sd} \ge 0 \end{aligned}\right\}, \quad t\in\{t_d\} \tag{8}$$

$$C_{it}^{m} = MT_{it}\left(1 - x_{it}\right), \quad t\in\{t_w\} \tag{9}$$

Constraints:

- Maintenance resources availability constraint:

$$u_{it} - u_{i(t-1)} \le x_{it}, \quad t\in\{t_w\} \tag{10}$$

- Coupling constraints between generation maintenance and unit commitment, which a unit cannot be online if it is on maintenance:

$$x_{it} + u_{it} \le 1, \quad t\in\{t_w\} \tag{11}$$

- Maximum outage duration constraint, which ensure that each unit is on maintenance outage for a pre-specified period over the year:

$$\sum_{t} x_{it} = T_i^{mo}, \quad t\in\{t_w\} \tag{12}$$

where T_i^{mo} is the pre-specified period of maintenance outage for generator *i* over the year.

- Continuous maintenance constraint, which require that the maintenance must be completed within the windows between the starting and ending times:

$$x_{it} - x_{i(t-1)} \le x_{i(t+T_i^{mo}-1)}, \quad t\in\{t_w\} \tag{13}$$

- Maximum number of units simultaneously in maintenance:

$$\sum_{i} x_{it} \le NM_t, \quad t\in\{t_w\} \tag{14}$$

where NM_t is maximum number of units on simultaneous maintenance of time *t*.

- Seasonal limitations, such as hydro energy constraint:

$$\sum_{t} g_{it} \le \sum_{t}\left(G_i^{MAX} HE_{it}\right), \; i\in\{\text{hydro gen.}\}, t\in\{t_d\} \tag{15}$$

where HE_{it} is hydro energy availability factor for a hydro unit *i* of time *t*. It represents the dependency of hydro generators on water availability in the reservoir over a period of time [12].

- Generation capability constraint:

$$G_i^{MIN}\left(1 - x_{it}\right) \le g_{it} \le G_i^{MAX}\left(1 - x_{it}\right), \quad t\in\{t^w\} \tag{16}$$

- CO_2 allowance market bidding constraint:

$$\sum_{t} k_i g_{it} \le A_{it} + OS_{it} + A_{it}^{ow}, \quad t\in\{t^q\} \tag{17}$$

$$\sum_{t} OS_{it} \le \sum_{t} 0.033 k_i g_{it}, \quad t\in\{t_q\} \tag{18}$$

where A_{it}^{ow} is the amount of allowances initially owned by firm *i* of time *t*, and it is defined as:

$$A_{i(t+1)}^{ow} = A_{it} + A_{it}^{ow} + OS_{it} - \sum_{t} k_i g_{it}, \quad t\in\{t_w\} \tag{19}$$

C. Lower Level Optimization Problem Formulation

(1) ***ISO Maintenance Clearing Subproblem***: GenCos are independently responsible for generation maintenance, and they submit the maintenance schedule to ISO, which coordinates with market participants to improve the security of electricity services and reduce the likelihood of blackouts. ISO solves the following optimization problem to minimize the cost of maintenance and unserved energy, while maintaining the balance between generation and load. The subproblem can be formulated as the following problem:

$$\begin{aligned} \min_{g_{it},} \quad & \sum_{t\in\{t_w\}} \left(C_{it}^{m} + C^{ue} UE_{it} \right) \\ s.t. \quad & \sum_{i,t} g_{it} + UE_{it} = \sum_{i} D_{it}, \quad t\in\{t_w\} \end{aligned} \tag{20}$$

where, C^{ue} is cost of unserved energy, UE_{it} is unserved energy, and D_{it} is total load at node i of time t.

(2) ***ISO UC and OPF Subproblem***: The short-term (daily/weekly) UC problem can be formulated in MILP formulation [11]. The ***Objective Function*** is:

$$\min_{g_{it}} \sum_{i} \sum_{t\in\{t_d\}} \left\{ C_{it}^{p} + C_{it}^{su} + C_{it}^{sd} \right\} \tag{21}$$

Constraints:

- Power balance constraint:

$$\sum_i g_{it} = \sum_i D_{it}, \quad t\in\{t_d\} \tag{22}$$

- System spinning and operating reserve constraints:

$$\sum_i r_{it}^{s} \ge R_t^{s}, \quad t\in\{t_d\} \tag{23}$$

$$\sum_i r_{it}^{o} \ge R_t^{o}, \quad t\in\{t_d\} \tag{24}$$

where, r_{it}^{s}/r_{it}^{o} are spinning/operating reserve at node i of t, R_{it}^{s}/R_{it}^{o} are required spinning/operating reserve at node i of t.

- Maximum spinning and operating reserve limit constraints:

$$r_{it}^{s} \le R_t^{s} u_{it}, \quad \forall i, t\in\{t_d\} \tag{25}$$

$$r_{it}^{o} \le R_t^{o} u_{it}, \quad \forall i, t\in\{t_d\} \tag{26}$$

- Generation unit capacity limit constraints:

$$G_i^{MIN} u_{it} \le g_{it}, \quad \forall i, t\in\{t_d\} \tag{27}$$

$$g_{it} + r_{it}^{s} + r_{it}^{o} \le G_i^{MAX} u_{it}, \quad \forall i, t\in\{t_d\} \tag{28}$$

- Ramping rate limit constraints:

$$g_{it} - g_{i(t-1)} \le MaxInc_i, \quad \forall i, t\in\{t_d\} \tag{29}$$

$$g_{it} - g_{i(t-1)} \ge -MaxDec_i, \quad \forall i, t\in\{t_d\} \tag{30}$$

where $MaxInc_i/MaxDec_i$ are maximum ramping rate for increasing/decreasing generation output of generator i.

- Minimum ON/OFF time limit constraints:

$$\left(Y_{i(t-1)}^{ON} - T_i^{ON}\right)\left(u_{i(t-1)} - u_{it}\right) \ge 0, \quad \forall i, t\in\{t_d\} \tag{31}$$

$$\left(Y_{i(t-1)}^{OFF} - T_i^{OFF}\right)\left(u_{it} - u_{i(t-1)}\right) \ge 0, \quad \forall i, t\in\{t_d\} \tag{32}$$

where $Y_{it-1}^{on}/Y_{it-1}^{off}$ are time duration for generator i to stay ON/OFF from beginning of time t-1, T_i^{on}/T_i^{off} are required time duration after generator i startup/shut down.

- Transmission flow limit constraint:

$$\sum_i PTDF_{ki}\left(g_{it} - D_{it}\right) \le F_k^{\max}, \quad \forall k, t\in\{t_d\} \tag{33}$$

where $PTDF_{ki}$ is the power transfer distribution factor, F_k^{max} is the power flow limit of branch k.

The solutions of UC problem will provide the commitment of generation units. Based on this, solution of the OPF problem hourly will lead to information on the generation dispatch and LMP. The ***Objective Function*** of OPF is:

$$\min_{g_{it}} \sum_{i,t\in\{t_d\}} \left(\alpha_i g_{it} + \frac{1}{2}\beta_i g_{it}^2 \right) \tag{34}$$

Constraints:

- Power balance constraint:

$$\sum_i g_{it} - \sum_i D_{it} = 0, \quad (\lambda_t) \quad t\in\{t_d\} \tag{35}$$

- Generation unit capacity limit constraints:

$$G_i^{MIN} u_{it} \le g_{it} \le G_i^{MAX} u_{it}, \quad t\in\{t_d\} \tag{36}$$

- Transmission flow limit constraint:

$$\sum_i GSF_{k-i}\left(g_{it} - D_{it}\right) \le F_k^{\max}, \ (\mu_{kt}) \quad \forall k, t\in\{t_d\} \tag{37}$$

where GSF_{k-i} is generator shift factor, μ_{kt} is dual variable of branch power flow limit constraint, and λ_t is dual variable of power balance constraint. Then LMP can be expressed as:

$$\begin{aligned} p_{it}^{e} &= LMP_{it} = LMP_{it}^{energy} + LMP_{it}^{cong} \\ &= \lambda_t + \mu_{kt} \sum_i GSF_{k-i}, \quad t\in\{t_d\} \end{aligned} \tag{38}$$

(3) ***CO₂ Allowance Market Clearing Subproblem***: GenCos decide their bidding amounts in the upper level problem, and send to lower level problem as parameters for market clearing. The CO_2 allowance market clearing price is obtained by solving the optimization problem (4).

The three-year GSP is formulated as a MIBLP problem.

$$\begin{aligned} \max_{g_{it}, x_{it}, q_{it}, OS_{it}} \quad & \sum_{t\in\{t_d\}} \left\{ \lambda_{it}^{e} g_{it} - C_{it}^{p} - C_{it}^{su} - C_{it}^{sd} \right\} - \sum_{t\in\{t_w\}} C_{it}^{m} \\ & - \sum_{t\in\{t_q\}} \left\{ \lambda_t^{co_2} A_{it} + C_{it}^{os} OS_{it} \right\} \\ s.t. \quad & \text{Generation Scheduling \& Bidding Constraints (2-3,7-19)} \\ & \text{ISO Maintenance Clearing Subproblem (20)} \\ & \text{ISO Unit Committment Subproblem (21-33)} \\ & \text{ISO Economy Dispatch Subproblem (34-38)} \\ & CO_2 \ \text{Allowance Market Clearing Subproblem (4)} \end{aligned} \tag{39}$$

The global optimal solutions of continuous variables of CO_2 allowance price $\lambda_t^{co_2}$, LMP p_{it}^{e} and generation dispatch g_{it}, binary variables of unit commitment u_{it} and generation maintenance schedule x_{it}, and integer variables of allowance dispatch A_{ft} and offsets usage OS_{ft} are obtained by solving this MIBLP problem with the methodology in the next section.

D. Algorithm

In the literature, there are few methods for a restricted class of Bi-Level Linear Programming problems. For example, no integer decision variable is involved in the lower level problem. There are no direct applications of the previous work on MIBLP problems. Based on Benders decomposition and transformation procedure [13], a novel methodology is proposed in [11]. The algorithm is described in the following.

Step 1: Divide the MIBLP problem into one Restricted Master Problem (RMP) and several Slave Problems (SPs) by fixing binary variables. In the initial step, RMP will only have the objective, and constraints are added in future iterations from the cut of solving SP. RMP will provide an upper bound.

Step 2: Transform the SP problem to a Linear Problem with Complementarity Constraints (LPCC), and solve it. SP is the restricted MIBLP, and it provides a lower bound. The decomposition technique allows parallel computation of solving multiple SPs.

Step 3: From the solution of LPCC problem, construct the LP problem. If solution is unbounded, add the *Feasibility Cut*; if solution is bounded, which provides a lower bound, and restricts RMP, add the *Optimality Cut*; if solution is bounded, which provides a lower bound, but does not restrict RMP, add the *Integer Exclusion Cut*. Then go to step 4.

Step 4: Solve RMP with an added cut, and obtain an updated upper bound. Find the difference between upper bound and lower bound. If it is within the tolerance, stop; otherwise, update the SP by setting constraint of current binary variable and go back to Step 2.

The proposed solution methodology leads to an optimal solution in an efficient way. The decomposition technique is essential for large-scale problems, and the transformation procedure validates the use of KKT conditions and transforms the MIBLP into two single level problems. Therefore, the proposed algorithm outperforms traditional enumeration or reformulation techniques in both quality and computational efficiency. The detailed derivations and comparison with traditional methods can be referred to [11].

IV. NUMERICAL RESULTS

The PJM 5-Bus System is used for illustration of the proposed MIBLP model and solution methodology, as shown in Fig. 5. It is assumed that all five GenCos participate in the electricity market and CO_2 allowance market. The seven-week generation maintenance scheduling of GenCo 1, daily unit commitment and hourly economic dispatch, and one CO_2 allowance market auction with three bidding strategies of GenCo 1 are considered in this case. It is assumed GenCo 1 makes its own decision, taking as given other GenCo decisions on the bidding quantity in CO_2 allowance market.

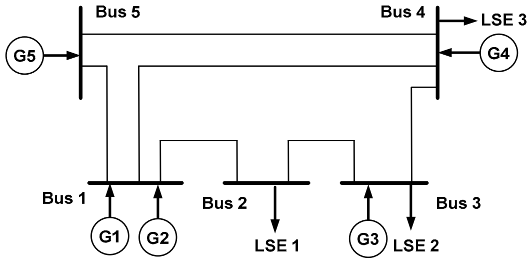

Fig. 5. PJM 5-bus system

A. System Data

The system topology, branch data, generation data, load data, GenCos' bidding offers in the electricity market, maintenance limit and CO_2 bidding offers of GenCo 1 are given in Tables 1-5 and Fig. 6.

B. Simulation Results

The comparison of GenCo 1's profit under different maintenance schedules and bidding strategies is shown in Fig. 7. In the base case, GenCo 1 only participates in the electricity market, and obtains the highest profit. When GenCo 1 participates in both electricity market and CO_2 allowance market, it receives less profit and the profits are different using various bidding strategies. This is due to the fact that GenCo 1 will spend more money in paying for the CO_2 allowance to cover the emission from generating electricity. Also, seven maintenance schedules and three bidding strategies result in different profits.

TABLE I
BRANCH DATA

Branch	From Bus	To Bus	Reactance X (p.u.)	Limit (p.u.)
1	1	2	0.0281	2.50
2	1	4	0.0304	1.5
3	1	5	0.0064	4
4	2	3	0.0108	3.5
5	3	4	0.0297	2.4
6	4	5	0.0297	2.4

TABLE II
DATA OF GENERATOR CHARACTERISTIC

Gen.	Bus	Fixed cost ($/hr)	Startup cost ($)	Shutdown cost ($)	Ramp up limit	Ramp down limit
1	1	50	100	20	1.2	1.4
2	1	60	150	20	1.2	1.4
3	3	70	200	20	0.8	1
4	4	150	400	20	1	1.2
5	5	50	120	20	1	1.2

TABLE III
GENCOS' ELECTRICITY BIDDING OFFERS/PRODUCTION COST ($/P.U.-HR)

Gen.	Block 1	Block 2	Block 3	Price 1	Price 2	Price 3
1	0.2	0.3	0.2	13	14	16
2	0.2	0.3	0.3	12	13	16
3	0.4	1	0.4	15	18	20
4	0.6	1	0.4	16	18	21
5	0.2	0.3	0.2	13	14	16

TABLE IV
MAINTENANCE LIMIT OF GENCO 1

Equipment	From Bus	To Bus	Windows	Duration (hrs)	Cost ($/hr)
G1	1	/	Mon. – Sun.	168	84

TABLE V
CO_2 ALLOWANCE BIDDING OFFERS OF GENCO 1

Strategy	q (p.u.)	λ^{CO2} ($/p.u.)
1	11000	1.60
2	12000	1.62
3	13000	1.65

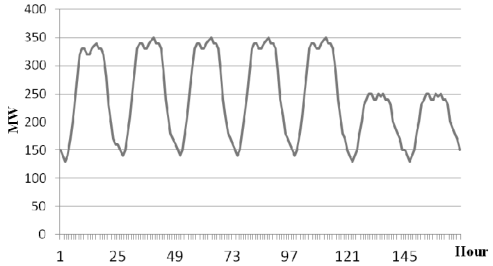

Fig. 6. One-week load data

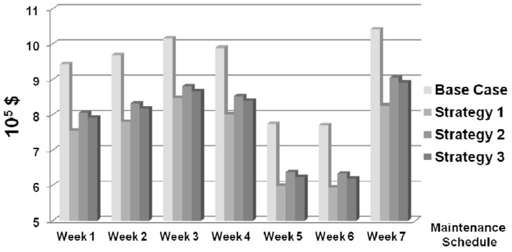

Fig. 7. Comparison of profits for GenCo 1

The comparison of profits under different maintenance schedules and bidding strategies are shown in Fig. 8 and Fig. 9. Under different maintenance schedules, the profits are different, and they change in the similar pattern with different CO_2 allowance bidding strategies. As shown in Fig. 9, neither Strategy 1 nor Strategy 3, which represents bidding too conservatively or aggressively, will bring the highest profit. In contrast, the medium bidding strategy (Strategy 2) can bring the optimal profit. Also optimal maintenance schedule will change with the different CO_2 allowance bidding strategy.

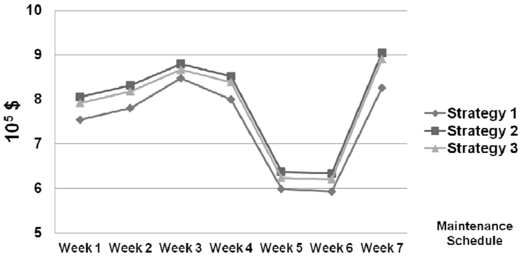

Fig. 8. Comparison of profits under different maintenance schedules

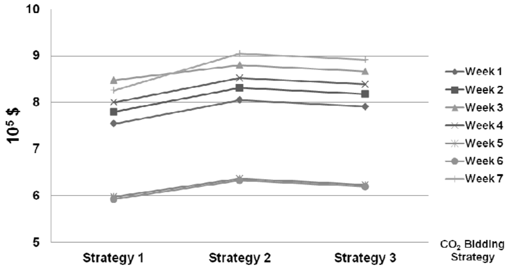

Fig. 9. Comparison of profits under different bidding strategies

The comparison of GenCo1's generation outputs under different bidding strategies and maintenance schedules is shown in Fig. 10. When GenCo1 has enough allowances under bidding strategy 2 or 3, it will have similar generation output. However, if GenCo1 does not have enough CO_2 allowances under bidding Strategy 1, its generation output will decrease a lot compared to the base case. Similar to the result of GenCo 1's profit, its generation output will change in different patterns under different maintenance schedules and bidding strategies. There is also a difference that when GenCo 1 has enough CO_2 allowance, it can actively participate in the electricity market and have the similar dispatch level as in the base case. However, GenCo 1 has to consider the cost of purchasing the CO_2 allowances, which will affect its profit, as shown in Fig. 9.

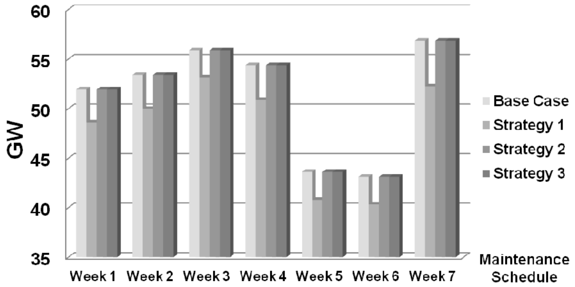

Fig. 10. Comparison of generation outputs for GenCO 1

The profit under optimal maintenance scheduling and CO_2 allowance bidding strategy is shown in Fig. 11. It is shown that Strategy 2 is the best bidding strategy, which means GenCo1 should not bid too many allowances (Strategy 3) or too few allowances (Strategy 1). The optimal bidding strategy can be obtained by solving the proposed optimization problem.

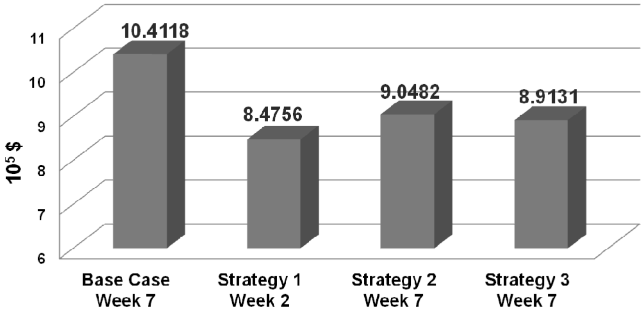

Fig. 11. Optimal maintenance scheduling & CO_2 allowance bidding strategy

C. Result Analysis

When a GenCo participate in CO_2 allowance market, it makes the decision of bidding amount based on the expectation of other GenCos' bidding offers. From the simulation results, it is observed that the optimal maintenance scheduling will be changed considering different CO_2 allowance bidding strategies, which are different in the bidding amount. Under three bidding strategies, which correspond to small, medium and large (can be used in secondary market) amount of allowances, GenCos will have different profits. Bidding strategy of either small or large amount of allowances does not optimize the profit. There is an optimal bidding strategy for a GenCo given its own estimation of bidding price. The optimal bidding strategy is connected with optimal maintenance scheduling. When the information or expectations change, the optimal bidding strategy will be different. GenCos need to consider the maintenance scheduling and CO_2 allowance bidding together in order to maximize their profits. Based on the proposed model, GenCos will be able to determine their optimal midterm generation maintenance scheduling and CO_2 emission allowance bidding strategy participating in both electricity market and CO_2 allowance market. The MIBLP model of new GSP together with the proposed solution methodology can provide valuable information to assist GenCos in their decision making.

D. Discussions

In the formulation of Cournot Equilibrium module for CO_2 allowance market, GenCos solves the optimization problem to decide its bidding offer in order to maximize its own profit, which equals to its revenue from selling energy to electricity market minus its cost of production, purchasing CO_2 allowances, and using offsets. The revenue obtained from electricity market is decided by the electricity price and GenCo's generation output level. Accurate information can only be achieved by solving the short-term unit commitment and economic dispatch in electricity market.

This new problem includes several generation scheduling problems under different time horizons. In the three-year CO_2 allowance compliance period, GenCos need to consider the quarterly auction in CO_2 allowance market, the midterm generation maintenance scheduling and short-term unit commitment to maintain the adequacy in midterm planning and security in short-term operation planning. Therefore, within the time horizon of three-month CO_2 allowance auction, the proposed algorithm is focused on the midterm generation maintenance scheduling. Short-term unit commitment and economic dispatch are considered to provide the accurate solution of electricity price and generation output level. But the bidding strategies of GenCos participation in electricity market are neglected, since our focus is on the midterm time horizon.

However, detailed formulation could be possibly simplified by using forecasted electricity prices. In the current model, the accurate information of electricity price and generation output level is obtained by solving the unit commitment and economy dispatch problems, which leads to much complexity due to the involvement of various integer and binary decision variables. If the electricity price is achieved using forecasting tools, then generation output level can be calculated based on GenCos' production cost curve, which assumes that GenCos bid based on their true cost curves. Based on these two assumptions, four subproblems in the lower lever of the proposed module can be reduced to two subproblems of ISO maintenance schedule clearing and CO_2 allowance market clearing. Then the complexity of the problem will be greatly reduced to one group of binary decision variables for generator maintenance scheduling. The simplification leads to loss of insight into GenCos' interactions between the two markets.

V. CONCLUSION

Carbon mitigation policies, such as CO_2 cap-and-trade, help to reduce consumption in traditional energy and promote to shift to renewable energy resources. This paper addresses the challenging issue of generation scheduling taking into account new environmental considerations. The CO_2 allowance market is formulated as the Cournot equilibrium model. Practical market rules, such as those in RGGI, are considered in the developed model. Then, the emission-constrained GSP in the three-year CO_2 allowance compliance period, involving generation maintenance scheduling, unit commitment and CO_2 cap-and-trade, is investigated. Based on the proposed model, GenCos are able to know the amount and price of CO_2 allowances to make bidding decisions in the electricity market, while they bid to CO_2 allowance market based on the information of electricity price and scheduled generation commitment and dispatch. With this information, GenCos will be able to determine their optimal midterm operation planning and short-time operation schedules participating in both electricity market and CO_2 allowance market. In the future work, the proposed model will be tested with data and scenarios from large-scale power systems.

VI. DISCLAIMER

This study reflects the views of the authors and not the views of their company or affiliations.

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