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An Optimal CO_2 Saving Dispatch Model for Wholesale Electricity Market Concerning Emissions Trade

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Abstract: Deep CO_2 mitigation provides a challenge to fossil fuel-fired power industry in liberalized electricity market process. To motivate generator to carry out mitigation action, this article proposed a novel dispatch model for wholesale electricity market under consideration of CO_2 emission trade. It couples carbon market with electricity market and utilizes a price-quantity uncorrelated auction way to operate both CO_2 allowances and power energy trade. Specifically, this CO_2 saving dispatch model works as a dynamic process of, (i) electricity and environment regulators coordinately issue regulatory information; (ii) initial CO_2 allowances allocation through carbon market auction; (iii) load demands allocation through wholesale market auction; and (iv) CO_2 allowances submarket transaction. This article builds two stochastic mathematical programmings to explore generator's auction decision in both carbon market and wholesale market, which provides its optimal price-quantity bid curve for CO_2 allowances and power energy in each market. Through piece-wise adding up individual demand curve (supply curve) and matching with total supplied allowances (load demanded), market equilibrium is reached. Under this dispatch model, price upper-bound of bid allowances of generators is upward ordered and price lower-bound of bid electricity is downward ordered, according to their operational advantage from weak to strong. Meanwhile their bid electricity upper-bound gets respective capacity constraint or market share regulation. These features imply that the proposed model can prompt economic dispatch, improve resources allocation efficiency and bring about CO_2 mitigation effect. Numerical simulations also verified the validity of this CO_2 saving dispatch model.

Keywords: Wholesale Electricity Market, CO_2 Emissions Trade, CO_2 Saving Dispatch, Economic Dispatch, Combinatorial Auction

1. Introduction

The United Nations Framework Convention on Climate Change (UNFCCC) has done huge efforts on controlling global CO_2 emission. Since UNFCCC passed the Paris Agreement at the end of 2015, last year saw the Katowice Climate Change Conference agreed on detail rules to urge its member countries to implement this Agreement. As a response to the Paris Agreement, Chinese government committed to abate 60%-65% of CO_2 emissions in 2030 year in accordance with its 2005 level. Electricity industry, featured as the largest emission sector in China (for example, in 2013 national coal-fired generation shared 73.8% of produced electricity thereof contributed to 42% of total CO_2 emissions), is undergoing liberalized market reformation. It is a challenge to generators to carry out CO_2 abatement under electricity market reforming process.

In line with competitive degree in electric power system, electricity market structure may be segmented into monopoly market, purchase-agent market, wholesale competition market and retail competition market [1]. Concerning Chinese electricity market reforming progress the State Electricity Regulatory Commission (SERC) suggests that, purchase-agent market is a transforming structure, wholesale market is a goal structure, and retail competition market is the final structure [2]. However, in recent articles many researchers did not distinguish purchase-agent market from wholesale competition market.

In liberalized electricity market process, price regulation acts as a critical role to incorporate CO_2 emissions abatement

[3]. For example, through setting incentive price Australia electricity market design has taken renewable energy generation into dispatch schedule [4]. As renewable energy generation has characteristics of variability and uncertainty, Ela et al. [5] and Milligan et al. [6] suggest that pay-for-performance wholesale market design may promote independent system operator (ISO) to procure renewable electricity. Concerning current Germany energy-only market design (EOM), Keles et al. [7] and Bublitz et al. [8] hold that an EOM extended with a strategic reserve can enhance supply security in a market with high share of renewable electricity. To achieve CO_2 abatement goal stipulated in the Paris agreement, there is an urgent need for market design to increase the compatibility among electricity market and carbon market [9]. As reported by Hogan [10], successful electricity market design should be built on the principles of auction-based, environment-friendly and security-constrained economic dispatch.

In theory, combinatorial auction is extensively adopted to design both electricity market and carbon market to promote CO_2 abatement in power industry. Through efficient market design, the former may motivate power system economic dispatch then brings indirect abatement effect, correspondingly, the latter has a benefit of optimizing CO_2 allowances allocation hence gets direct abatement effect. Combinatorial auction allows bidder to bid on a combination of commodities rather than single-unit, and has an advantage to overcome the exposure problem in a multi-unit commodities auction that is an inherent requirement of bid decision in both electricity market and carbon market [11]. In recent literature, Zaidi et al. [12] introduce a combinatorial auction to efficiently allocate common energy storage system in a smart microgrid. Zaidi and Hong [13] design a combinatorial double auction mechanism to explore electricity trade among multiple microgrids.

In electricity market, uniform-price auction and pay-as-bid auction are known as two main kinds of combinatorial auction. Payment for winners of the former is settled as the bid price of the last in-merit dispatch order (i.e. uniform market clearing price, MCP), while the latter is settled as respective winner's bid price (i.e. pay-as-bid, PAB) [14]. PAB auction may dampen the market power, control tacit collusion, and reduce price volatility caused by load forecast bias [15-17]. However, under this auction generators are motivated to bid price higher than their marginal cost, therefore it is characterized as low efficiency [15, 18]. Contrast with PAB auction, MCP auction can incentivize generators to reveal their true cost information, as a consequence brings about equality and efficiency [18-19]. In Italy electricity market liberalized process, independent system operator (ISO) permitted generators to enjoy nondiscriminatory transmission service and the settlement implemented a uniform regional price. Beraldi el al. [20] simulates this market then support that MCP auction has benefits to reinforce system security and operational efficiency. In both Australia and New Zealand electricity market, there were a multi-round combinatorial auction in operation. In line with Contreras et al. [21], this auction can minimize power system cost. Contreras et al. [21] further make a comparison to social welfare change among the three kinds of auction: price-quantity uncorrelated single-round auction, price-quantity correlated single-round auction, price-quantity uncorrelated multi-round auction, suggesting that the latter is more efficient. Obviously, the higher efficiency of resources allocation in electricity market, the greater indirect CO_2 abatement effect is brought by economic dispatch pathway.

To incentivize generators to implement CO_2 mitigation under constraints of electricity supply balancing with load demand, based on literature [9, 10, 12, 18, 21], this paper developed a novel dispatch model for wholesale electricity market on condition of CO_2 emissions trade. It couples carbon market with electricity market and utilizes price-quantity uncorrelated multi-round auction to organize both CO_2 allowances and power energy trade. As seen in section 4, reserve price of generators is ordered in line with their operational advantage, meanwhile their maximum bid quantity is equal to either respective capacity constraint or market share regulation. Therefore, the proposed dispatch model can promote economic dispatch in a way avoiding economic withholding as well as physical withholding [1] in electricity market and bring about CO_2 mitigation effect, not only direct from carbon market but also indirect from electricity market.

The following part is organized as, Section 2 depicts assumptions and framework of the proposed CO_2 saving dispatch model. Section 3 analyzes price-quantity auction for CO_2 allowances allocation in carbon market. Section 4 explores price-quantity auction for power energy allocation in wholesale market as well as CO_2 submarket trade. To make an intuitive version of CO_2 mitigation effect, section 5 carries out a numerical simulation as well as a comparison among the proposed dispatch model, average allocating allowances dispatch model and average allocating load model. Finally, a brief conclusion is summarized in section 6.

2. Model Description

2.1. Assumptions

As seen in section 1, existing power dispatch model in wholesale market needs to be compatible with CO_2 abatement policies to motivate generator to reduce emissions. This article addresses the compatibility problem by making an optimal dispatch model for wholesale market under consideration of CO_2 emissions trade. To get model design more practical and be set on robust theoretical basis, it is necessary to emphasize the following assumptions:

i. The wholesale market is generation side open-up, regional grid company (or ISO) is the single purchaser, bidders are independent power producer (IPPs), and all loads are transacted through MCP auction way.
ii. Power system keeps balance between loads and

generations. The primary goal of power industry is to supply electricity to meet the demand for national economy development [22]. Elmaghraby [23] and Song et al. [24] also hold that a successful wholesale market design has a feature of all loads being dispatched.

iii. The wholesale market has *n* coal-fired generators and each owns one generation unit. Although the proposed CO_2 saving dispatch model can deal with the issue of generator owning multiple generation units, this assumption may simplify its fuel consumption function and avoid complex mathematical formulation.

iv. Dispatched electricity of generator is restricted by a fixed market share to avoid abusing market power.

v. Information is asymmetric and collusion is forbidden among generators and regulators. This means the cost information of generator is privacy, therein no generator can accurately predict market clearing price, both in CO_2 allowances auction process and in electricity auction process.

vi. Ancillary services, such as spinning reserve, operating reserve, frequency control, reactive power and black-start etc., are not concerned.

To analyze the proposed CO_2 saving dispatch model and optimize generator's decision making, variables are defined in section Nomenclature.

2.2. CO_2 Saving Dispatch Model

This section developed an optimal dispatch model for wholesale market coupled with emissions trade to incentivize generator to carry out CO_2 abatement. Its framework is described as follow:

Previously, market regulators proclaim the regulatory information. Concretely, electricity regulator needs to issue information on yearly load demand, grid line loss rate, electricity price restriction and market share regulation. Concerning electricity regulation, environment regulator releases CO_2 allowances cap, carbon price restriction, yardstick emission intensity, default emission penalty rate and CO_2 submarket transaction rate.

Then, environment regulator organizes initial CO_2 allowances trade in carbon market. As a necessary production factor, generators bid for allowances through the first sealed price-quantity MCP auction way. To leave more decision choices for allowances utilization and carry out power system CO_2 mitigation, generators may trade allowances after wholesale electricity transaction. In submarket, CO_2 allowances may be traded among generators or be purchased from environment regulator. For the former way, purchaser will be charged by additional transaction cost; for the latter way, it needs to pay the highest price composed of MCP, penalty and additional transaction cost.

Thereafter, electricity regulator and ISO organize wholesale market transaction by employing the MCP combinatorial auction approach.

In the end, environment regulator arranges carbon submarket transaction to fulfill CO_2 allowances allocation among generators.

This optimal dispatch model is a dynamic process being composed of "electricity regulatory information，environment regulatory information，generators bid for CO_2 allowances，generators bid for electricity and CO_2 submarket transaction". As seen in sections 3-5, it has a benefit to enhance compatibility between carbon market and wholesale electricity market, consequently may motivate generators to reduce CO_2 emissions on condition of electricity supply balancing with load demand.

As a main improvement, the proposed dispatch model applies the first sealed price-quantity combinatorial auction [25-27] to organize market transaction. In carbon market it has many advantages over CO_2 allocation free of charge, such as price discovery, avoiding windfall profits as well as carbon leakage problem [28-29]. In wholesale market it can improve market efficiency, promote economic dispatch and bring about indirect CO_2 mitigation effect. Setting floor and ceiling to price may overcome it fluctuating too much therein increase market stability, both in carbon market and in electricity market.

Emission intensity slack factor m_j, defined as $e_j\left(1+m_j\right) \equiv e$, acts as two roles: to incentivize generator controlling CO_2 intensity and to ensure power system reliability at a cost of emissions increase appropriately. Since yardstick intensity $e \equiv E^{(S)} / [W^{(D)} + W^{(Loss)}]$ does not include emissions caused by self-consumed electricity, if a generator has higher emission intensity over yardstick intensity (i.e., $m_j < 0$) then all its emissions will be charged with extra default emission penalty rate α. This regulatory rule tightens default emission penalty. Concerning respective Euro 40/tCO_2 and Euro 100/tCO_2 for default emissions in EU ETS first and second period, it holds the straining penalty tendency. This penalty rule may incentivize generator to improve operational management and invest in carbon capture and storage (CCS) technology.

To pursue expected profit, in both carbon market and electricity market generator needs to concern the profitability of CO_2 allowances. This means that generator needs to take CO_2 submarket possible transaction into consideration when making decision at each stage. As shown in Figure 1, generator may trade CO_2 allowances with other generators or directly purchase allowances from environment regulator. However, for the former way, purchaser will be charged with extra submarket charge rate β; for the latter way, it will pay the highest price composed of MCP, default emission fine rate α and submarket charge rate β. Since power system requires balancing generation and load demand in real time, during peak load period the ISO needs to meet load demand at a sacrifice of emissions increased appropriately. But in this case environment regulator may punish those generators whose CO_2 intensity is higher than yardstick intensity thus transfer part of their profit into social welfare.

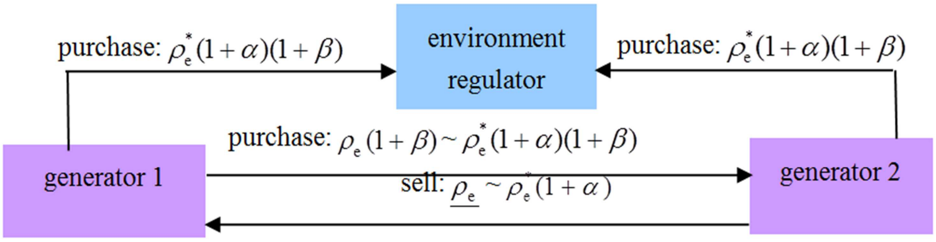

Figure 1. *Carbon submarket transaction: cost for purchaser and revenue for seller.*

Under this CO$_2$ saving dispatch model, generator not only needs to bid for CO$_2$ allowances but also needs to bid for power energy in a first sealed price-quantity uncorrelated MCP auction way. In auction terminology, each round is a homogenous commodity combinatorial auction [30-31], which is also main improvement of the new dispatch model, as a result of that, more efficient to resources allocation.

3. Initial CO$_2$ Allowances Trade

3.1. Generator's Decision Making in Initial Carbon Market

To produce electricity, generator needs to bid for CO$_2$ allowances in carbon market. Rationally, its decision on optimal price-quantity demand function is based on all available public or private information. In line with section 2.2 and assumptions (i) to (v), generator's decision can be modeled as the following stochastic math programming, of which objective function is maximization of expected profit, and constraints include technical restriction, price regulation and market share restriction. Since generator cannot get exact data on electricity price and operational active power at this stage, it may assume them as a uniform distribution stochastic variable in reasonable range. Note that in CO$_2$ submarket transaction, selling surplus allowances will not only be charged with extra transaction cost, but also suffer a probability of transaction failure. On the other hand, purchasing shortage allowances will pay higher price than MCP, despite from other generators or from environment regulator. Therefore the profitability of CO$_2$ allowances inclines it to be utilized as a production factor of generation, rather than a speculative instrument through market trade.

$$\max \pi_j = \frac{E_j}{e_j.(1+s_j)}.\int_{\underline{\rho_w}}^{\overline{\rho^w}} \rho_w.\phi(\rho_w)\,d\rho_w - E_j.\rho_{ej} - \int_{\underline{p_j}}^{\overline{p_j}}\left[\left(a_j+b_j.P_j+c_j.P_j^2\right).\frac{E_j}{e_j.P_j}.\rho_{cj}\right]\phi(P_j)\,dP_j + \min(0,m_j).E_j.\alpha.\rho_{ej} \quad (1)$$

$$\frac{E_j}{e_j.(1+s_j)} \le \tau.\frac{E^{(S)}}{e} \quad (2)$$

$$e_j.(1+m_j)=e \quad (3) \qquad \underline{P_j} \le P_j \le P_j^{(N)} \quad (4)$$

$$\underline{\rho_w} \le \rho_w \le \overline{\rho_w} \quad (5)$$

$$\phi(P_j)=\begin{cases}\dfrac{1}{P_j^{(N)}-\underline{P_j}}, \text{if}, \rho_w \in \left[\underline{P_j}, P_j^{(N)}\right] \\ 0, others\end{cases} \quad (6)$$

$$\phi(\rho_w)=\begin{cases}\dfrac{1}{\overline{\rho_w}-\underline{\rho_w}}, if, \rho_w \in \left[\underline{\rho_w}, \overline{\rho_w}\right] \\ 0, others\end{cases} \quad (7)$$

$$\underline{\rho_e} \le \rho_{ej} \le \overline{\rho_e} \quad (8)$$

$$E_j \ge 0$$

Eq. 1 shows that generator's expected revenue is the multiples of expected electricity price and selling electricity calculated as bid CO2 allowances. Its expected cost is composed of allowances cost, expected fuel cost and potential emission penalty. In line with literature [32-33], this article concerns quadratic fuel consumption function, i.e., $F_j(P_j)=a_j+b_j.P_j+c_j.P_j^2$. Eq. 2 is electricity market share regulation embodied in carbon market, meaning that potential selling electricity is no more than the amount determined by market share. Eqs. 6-7 are respective probability density function of operational active power and electricity price.

3.2. Generator's Demand Function

Through solving the above mathematical programming, generator's optimal CO$_2$ allowances bid curve is obtained.

In probability theory, suppose zero-probability event is equivalent to impossible event. Then Eqs. 4 and 5 are included in Eqs. 6 and 7, respectively. For convenience, denoting expected electricity price as $A \equiv \int_{\underline{\rho_w}}^{\overline{\rho^w}} \rho_w.\phi(\rho_w)\,d\rho_w$ and expected fuel cost per MWh as $B_j \equiv \Phi\left(\rho_{cj}, F_j(P_j)\right) = \rho_{cj}.\int_{\underline{p_j}}^{\overline{p_j}} \frac{F_j(P_j)}{P_j}\phi(P_j)\,dP_j$. Let's put Eqs. 3, 6 and 7 into Eq. 1, order marginal profit $d\pi_j/dE_j \ge 0$, thus optimal bid price curve is solved as

$$\rho_{ej} \le \rho_{ej}^{*} = \frac{\dfrac{A}{e_j\left(1+s_j\right)} - \dfrac{B_j}{e_j}}{1-\min\left(0, \dfrac{e}{e_j}-1\right)\alpha}$$
$$= \frac{\dfrac{\underline{\rho_w}+\overline{\rho_w}}{2e_j.\left(1+s_j\right)} - \dfrac{1}{e_j}\dfrac{\rho_{cj}}{P_j^{(N)}-\underline{P_j}}.\left[\left(a_j.In\left(P_j^{(N)}\right)+b_j.P_j^{(N)}+\dfrac{c_j}{2}.\left(P_j^{(N)}\right)^2\right)-\left(a_j.In\left(\underline{P_j}\right)+b_j.\underline{P_j}+\dfrac{c_j}{2}.\left(\underline{P_j}\right)^2\right)\right]}{1-\min\left(0, \dfrac{e}{e_j}-1\right).\alpha} \tag{9}$$

According to CO_2 submarket transaction rules specified in section 2.2, under optimal bid price constraint, generator's optimal bid allowances equals to its upper-bound[1], and vice versa. Taking Eq. 8 constraint into consideration, generator's optimal price-quantity bid curve in carbon market is

$$E_j = \begin{cases} \tau.\dfrac{E^{(S)}.e_j.\left(1+s_j\right)}{e}; bid \quad price: \underline{\rho_e} \le \rho_{ej} \le \min\left(\overline{\rho_e}, \rho_{ej}^{*}\right) \\ 0; bid \quad price: \varnothing \end{cases} \tag{10}$$

Given a deep exploration, generator's decision making is corresponding to the principles of incentive compatibility and individual rationality constraints [8, 10] in market design theory. As a consequence, all optimal bid curves get a Nash equilibrium in carbon market.

3.3. Initial CO_2 Allowances Allocation

For convenience, let's divide n generators into m sets according to isoquant marginal emission revenue of start-generation (MERS or ρ_{ej}^{*}), and define an index function as

$$i = i_{k_i} = \left\{\left(i, k_i\right) \middle| i = 1,2,\ldots,m; k_i = 1,2,\ldots,K_i; \rho_{e,i_1}^{*} = \ldots = \rho_{e,i_{k_i}}^{*} = \ldots = \rho_{e,i_{K_i}}^{*}; \forall \rho_{e,i}^{*} \ne \rho_{e,r}^{*}; r \ne i; 1 \le r, i \le m; 1 \le m, K_i \le n\right\}$$

where K_i is generator number of the i -th set.

Through adding up individual bid curve together, environment regulator gets the following demand curve in carbon market.

$$E^{(D)}\left(\rho_e\right) = \sum_{i=1}^{i^*}\sum_{k_i=1}^{K_i} E_{i_{k_i}} = \begin{cases} \sum\limits_{i=1}^{i^*}\sum\limits_{k_i=1}^{K_i} E_{i_{k_i}}, if\ \underline{\rho_e} \le \rho_e \le \min\left(\overline{\rho_e}, \rho_{e,i^*}^{*}\right) \\ \ldots \\ \sum\limits_{i}\sum\limits_{k_i=1}^{K_i} E_{i_{k_i}}, if\ \underline{\rho_e} \le \rho_e \le \min\left(\overline{\rho_e}, \rho_{e,i}^{*}\right), 1 \le i \le i^* \\ \ldots \\ \sum\limits_{k_1=1}^{K_1} E_{1_{k_1}}, if\ \underline{\rho_e} \le \rho_e \le \min\left(\overline{\rho_e}, \rho_{e,1}^{*}\right) \\ 0, others \end{cases} \tag{11}$$

Let demand equals to supply, the market equilibrium is reached (see Eq. 12). To incentivize generator to control CO_2 intensity in a way raising emission cost appropriately, environment regulator chooses upper-bound of emission critical price range (ECPR) as market clearing price (MCP). As seen in Eq. 13, ECPR is defined as the price interval where line $E^{(*)}$ is identified to line $E^{(D)}\left(\rho_e\right)$ or its immediate-up line $E^{(D)}\left(\rho_e\right)$ on $E-\rho_e$ plane.

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[1] Because in CO_2 submarket, to sell surplus allowances will suffer a probability of unsuccessful transaction; to purchase shortage allowances will bear higher price composed of MCP, submarket transaction charge rate and penalty rate, despite from other generator or from environment regulator.

$$\rho_e^* = \begin{cases} \min\left(\overline{\rho_e}, \rho_{e,i^{**}}^*\right); if\ E^{(*)} = E^{(S)} = \min\left(E^{(S)}, \sum_{i=1}^{i^*}\sum_{k_i=1}^{K_i} E_{i_{k_i}}\right); where\ \ 1 \le i^{**} \le i^*\ and \sum_{i=1}^{i^{**}-1}\sum_{k_i=1}^{K_i} E_{i_{k_i}} < E^{(*)} \le \sum_{i=1}^{i^{**}}\sum_{k_i=1}^{K_i} E_{i_{k_i}} \\ \min\left(\overline{\rho_e}, \rho_{e,i^*}^*\right); if\ E^{(*)} = \sum_{i=1}^{i^*}\sum_{k_i=1}^{K_i} E_{i_{k_i}} \end{cases} \tag{12}$$

Let's denote ECPR as $\sigma_{\left(i^{**},i^*\right)}$, it can be written as,

$$\sigma_{\left(i^{**},i^*\right)} = \begin{cases} \sigma_{i^{**}} = \left\{\rho_e \mid \min\left(\overline{\rho_e}, \rho_{e,i^{**}+1}^*\right) \le \rho_e \le \rho_e^*\right\}, if\ E^{(*)} = E^{(S)}, i.e., \rho_e^* = \min\left(\overline{\rho_e}, \rho_{e,i^{**}}^*\right) \\ \sigma_{i^*} = \left\{\rho_e \mid \underline{\rho_e} \le \rho_e \le \rho_e^*\right\}, if\ E^{(*)} = \sum_{i=1}^{i^*}\sum_{k_i=1}^{K_i} E_{i_{k_i}}, i.e., \rho_e^* = \min\left(\overline{\rho_e}, \rho_{e,i^*}^*\right) \end{cases} \tag{13}$$

Since ECPR upper-bound is equal to bid price upper-bound of marginal winner, ECPR pricing rule has a policy effect of transferring part of profit of marginal winner into social welfare as well as overcoming winner's curse [11, 13]. When allocating allowances among winners, environment regulator sets the rule as, (i) complete match generators having bid allowances where price is higher than ECPR upper-bound; (ii) average allocate the spare allowances among generators having bid allowances where price is at ECPR interval but no bid allowances where price is higher than ECPR upper-bound. The spare CO$_2$ allowances is calculated by Eq. (14). The ECPR allocation rule also has a policy effect to prior allocate CO$_2$ allowances to generators characterized as emission advantage (i.e., higher MERS).

$$(E^{(*)remain}) = E^{(*)} - \sum_{i=1}^{i^{**}-1}\sum_{k_i=1}^{K_i} E_{i_{k_i}} \tag{14}$$

4. Wholesale Electricity Market and CO$_2$ Submarket Trade

4.1. Generator's Decision Making in Wholesale Electricity Market

Through carbon market auction CO$_2$ allowances is allocated and its MCP price is determined, which alleviates decision uncertainty to bid electricity in wholesale market. As information on operational active power, purchase and sell price of CO$_2$ allowances in submarket are still unknown accurately, generator may assume these parameters are stochastic variables subject to a uniform distribution in appropriate range. In line with section 2.1, 2.2 and 3.3, generator's decision on bid curve in wholesale market can be modeled as the following stochastic math programming.

$$\begin{aligned} \max \pi_j = {} & W_j.\rho_{wj} - \max\left(\Gamma_j, 0\right).\left[\int_{-\infty}^{+\infty} \rho_e^*(1).\phi\left(\rho_e^*(1)\right) d\rho_e^*(1)\right].prob\left(X = 0/\Gamma_j > 0\right) - E_j^*.\rho_e^* - \max\left(\Gamma_j, 0\right).\rho_e^*.(1+\alpha).(1+\beta).prob\left(X = 1/\Gamma_j > 0\right) + \\ & \max\left(-\Gamma_j, 0\right).\left[\int_{-\infty}^{+\infty} \rho_e^*(2).\phi\left(\rho_e^*(2)\right) d\rho_e^*(2)\right].prob\left(X = 0/\Gamma_j \le 0\right) - \int_{-\infty}^{+\infty}\left[\frac{a_j + b_j.P_j + c_j.P_j^2}{P_j}.W_j.\left(1+s_j\right).\rho_{cj}\right].\phi\left(P_j\right) dP_j \end{aligned} \tag{15}$$

st.

$$W_j \le \tau.W^{(D)}.\left(1+s\right) \tag{16}$$

$$\underline{P_j} \le P_j \le P_j^{(N)} \tag{17}$$

$$\underline{\rho_w} \le \rho_{wj} \le \overline{\rho_w} \tag{18}$$

$$\phi\left(P_j\right) = \begin{cases} \dfrac{1}{P_j^{(N)} - \underline{P_j}} & if \\ \rho_w \in \left[\underline{P_j}, P_j^{(N)}\right] \\ 0, & others \end{cases} \tag{19}$$

$$\varphi\left(\rho_e^*(1)\right) = \begin{cases} \dfrac{1}{(1+\beta).\left(\rho_e^*.(1+\alpha) - \underline{\rho_e}\right)}, & if \\ \rho_e^*(1) \in \left[\underline{\rho_e}.(1+\beta), \rho_e^*.(1+\beta).(1+\alpha)\right] \\ 0, & others \end{cases} \tag{20}$$

$$\varphi\left(\rho_e^*(2)\right) = \begin{cases} \dfrac{1}{\rho_e^*.(1+\alpha) - \underline{\rho_e}} & if \\ \rho_e^*(2) \in \left[\underline{\rho_e}, \rho_e^*.(1+\alpha)\right] \\ 0, & others \end{cases} \tag{21}$$

$$\Gamma_j = W_j.\left(1+s_j\right).e_j - E_j^* \tag{22}$$

$$prob\left(X = x/\Gamma_j > 0\right) = \begin{cases} 1/2, & if \quad x=0 \quad or \quad 1 \\ 0, & others \end{cases} \tag{23}$$

$$prob\left(X = x/\Gamma_j \le 0\right) = \begin{cases} 1/2, & if \quad x=0 \quad or \quad 1 \\ 0, & others \end{cases} \tag{24}$$

$$W_j \ge 0$$

As shown in Eq. 15, generator's expected revenue is sourced from selling electricity and surplus CO_2 allowances, meanwhile expected cost is caused by fuel consumption, initial CO_2 allowances purchase as well as shortage allowance purchase from other generators or environment regulator. Eq. 16 is constraint of market share regulation. Eqs. 19, 20 and 21 respective indicate probability density function of operational active power, CO_2 purchase price and selling price among generators. Eqs. 23 and 24 are two 0-1 stochastic variables specifying CO_2 submarket transaction decision, where $\Gamma_j > 0$ means purchase, $\Gamma_j \le 0$ means sell, $x=0$ denotes transaction among generators, and $x=1$ denotes direct purchase from environment regulator. For example, event $X = 1/\Gamma_j \le 0$ implies that selling surplus CO_2 allowances suffers a failure.

4.2. Generator's Supply Function

To get optimal price-quantity bid curve in wholesale market, this section solves the above mathematical programming. Similar to section 3.2, Eq. 17 is included in Eq. 19. Let's put Eqs. 19-24 into Eq. 15 and order marginal profit $d\pi_j/dW_j \ge 0$, meanwhile concern constraint Eq. 16 and non-negative condition, then optimal bid price curve is solved as

$$\rho_{wj} \begin{cases} \ge \frac{1}{4}\left[\underline{\rho_e} + \rho_e^*.(1+\alpha)\right].\left(1+s_j\right).e_j + B_j.\left(1+s_j\right) \underline{\underline{\ sign\ }} \rho_{wj}^{(1)*} \quad if \quad W_j < \dfrac{E_j^*}{\left(1+s_j\right).e_j} \\ \ge \frac{1}{4}(1+\beta).\left[\underline{\rho_e} + \rho_e^*.(1+\alpha)\right].\left(1+s_j\right).e_j + \frac{1}{2}\rho_e^*.(1+\alpha).(1+\beta).\left(1+s_j\right).e_j + B_j.\left(1+s_j\right) \underline{\underline{\ sign\ }} \rho_{wj}^{(2)*} \quad if \quad W_j > \dfrac{E_j^*}{\left(1+s_j\right).e_j} \\ \ge B_j.\left(1+s_j\right) \underline{\underline{\ sign\ }} \rho_{wj}^{(3)*} \quad if \quad W_j = \dfrac{E_j^*}{\left(1+s_j\right).e_j} \end{cases} \tag{25}$$

For convenience, sign $W_j^* = E_j^*/e_j.\left(1+s_j\right)$. Considering constraints Eqs. 16, 18 and non-negative condition,

if $W_j < W_j^*$, then bid price-quantity is $\max\left(\underline{\rho_w}, \rho_{wj}^{(1)*}\right) \le \rho_{wj}^{(1)} \le \overline{\rho_w}$ and $W_j^{(1)*} \in \left[0, \min\left(W_j^{*-}, P_j^N.\left(8760-T_j\right), \tau.W^{(D)}.(1+s)\right)\right]$;

if $W_j > W_j^*$, then bid price-quantity is $\max\left(\underline{\rho_w}, \rho_{wj}^{(2)*}\right) \le \rho_{wj}^{(2)} \le \overline{\rho_w}$ and $W_j^{(2)*} \in \left[W_j^{*+}, \min\left(P_j^N.\left(8760-T_j\right), \tau.W^{(D)}.(1+s)\right)\right]$;

if $W_j = W_j^*$, then bid price-quantity is $\max\left(\underline{\rho_w}, \rho_{wj}^{(3)*}\right) \le \rho_{wj}^{(3)} \le \overline{\rho_w}$ and $W_j^{(3)*} = \min\left(W_j^*, P_j^N.\left(8760-T_j\right)\right)$.

To put the above three items together, generator's optimal price-quantity bid curve is

$$W_j \begin{cases} \in \left\{\min\left(W_j^*, P_j^N.\left(8760-T_j\right)\right)\right\} \underline{\underline{sign}}\ \omega_{j1}; bid \quad price: \max\left(\underline{\rho_w}, \rho_{wj}^{(3)*}\right) \le \rho_{wj} \le \overline{\rho_w} \underline{\underline{sign}}\ \kappa_{j1} \\ \in \left[0, \min\left(W_j^{*-}, P_j^N.\left(8760-T_j\right), \tau.W^{(D)}.(1+s)\right)\right] \cup \left\{\min\left(W_j^*, P_j^N.\left(8760-T_j\right)\right)\right\} \underline{\underline{sign}}\ \omega_{j2} bid \quad price: \max\left(\underline{\rho_w}, \rho_{wj}^{(1)*}\right) \le \rho_{wj} \le \overline{\rho_w} \underline{\underline{sign}}\ \kappa_{j2} \\ \in \left[0, \min\left(W_j^{*-}, P_j^N.\left(8760-T_j\right), \tau.W^{(D)}.(1+s)\right)\right] \cup \left[W_j^{*+}, \min\left(P_j^N.\left(8760-T_j\right), \tau.W^{(D)}.(1+s)\right)\right] \cup \left\{\min\left(W_j^*, P_j^N.\left(8760-T_j\right)\right)\right\} \underline{\underline{sign}}\ \omega_{j3}; \text{bid price}: \max\left(\underline{\rho_w}, \rho_{wj}^{(2)*}\right) \le \rho_{wj} \le \overline{\rho_w} \underline{\underline{sign}}\ \kappa_{j3} \\ \in \varnothing; \quad others \end{cases} \tag{26}$$

Through a deep exploration, bid electricity of generators having strengths on power production (i.e., lower marginal power cost of start-generation, MPCS or ρ_{wj}^*) will be prior dispatched. Moreover, changing bid electricity interval or bid price interval in Eq. 26 will inevitably cause an expected profit loss. Eq. 26 means that generator's supply function may overcome speculation through physical withholding or economic withholding [17, 22] hence holds the intrinsic requirement of economic dispatch, in this way brings about indirect CO_2 saving effect. Similar to carbon market auction, all individual supply functions reach a Nash equilibrium in wholesale market.

4.3. Electricity Dispatch and CO_2 Submarket Trade

Similarly, let's separate n generators as M sets according to isoquant MPCS and define the following index function.

$$I = I_{k_I} = \left\{\left(I, k_I\right) \middle| I = 1,2,...,M; k_I = 1,2,...,K_I; \rho_{w,I_1}^* = ... = \rho_{w,I_{k_I}}^* = ... = \rho_{w,I_{K_I}}^*; \forall \rho_{w,I}^* \ne \rho_{w,r}^*; r \ne I; 1 \le r, I \le M; 1 \le M, K_I \le n\right\}$$

where K_I is generator number of the I -th set.

Generators deliver their price-quantity bid curve to independent system operator (ISO) in a sealed combinatorial auction way. Through piecewise aggregation of individual supply function, ISO forms the following market supply function.

$$W^{(S)}\left(\rho_w\right) \in \begin{cases} \left[\sum_{I\in\mu_{\max}}\sum_{k_I=1}^{K_I}\sum_{v=1}^{3}\min\omega_{\left(I_{k_I},v\right)}, \sum_{I\in\mu_{\max}}\sum_{k_I=1}^{K_I}\sum_{v=1}^{3}\max\omega_{\left(I_{k_I},v\right)}\right] if\ \rho_w^{(\mu_{\max})} \le \rho_w \le \overline{\rho_w}\ where\ \mu_{\max} = \left\{ I \middle| I=1,\ldots,I^*\ and\ \rho_w^{(\mu_{t_{\max}})} = \max\bigcup_{I=1}^{I^*}\bigcup_{v=1}^{3}\left(\min_{\left(\Theta_{I,v}\neq\varnothing\right)}\kappa_{I,v}\right)\right\}; \\ \cdots \\ \left[\sum_{I\in\mu_t}\sum_{k_I=1}^{K_I}\sum_{v=1}^{3}\min\omega_{\left(I_{k_I},v\right)}, \sum_{I\in\mu_t}\sum_{k_I=1}^{K_I}\sum_{v=1}^{3}\max\omega_{\left(I_{k_I},v\right)}\right] if\ \rho_w^{(\mu_t)} \le \rho_w \le \overline{\rho_w} where \mu_t = \left\{ I \middle| \begin{array}{l} I=1,\ldots,I^*, and \\ \rho_w^{(\mu_t)} = \left[\min\bigcup_{I=1}^{I^*}\bigcup_{v=1}^{3}\left[\min_{\left(\Theta_{I,v}\neq\varnothing\right)}\kappa_{I,v}\right]\right] \backslash \bigcup_{\gamma=0}^{t-1}\left\{\rho_w^{(\mu_\gamma)}\right\} \end{array}\right\}; \begin{array}{l} 1\le t\le 3I^*, \\ \rho_w^{(\mu_0)}=\varnothing; \end{array} \\ \cdots \\ \left[\sum_{I\in\mu_1}\sum_{k_I=1}^{K_I}\sum_{v=1}^{3}\min\omega_{\left(I_{k_I},v\right)}, \sum_{I\in\mu_1}\sum_{k_I=1}^{K_I}\sum_{v=1}^{3}\max\omega_{\left(I_{k_I},v\right)}\right] if\ \rho_w^{(\mu_1)} \le \rho_w \le \overline{\rho_w} where \mu_1 = \left\{ I \middle| \begin{array}{l} I=1,\ldots,I^*, and \\ \rho_w^{(\mu_1)} = \min\bigcup_{I=1}^{I^*}\bigcup_{v=1}^{3}\left[\min_{\left(\Theta_{I,v}\neq\varnothing\right)}\kappa_{I,v}\right] \end{array}\right\}; \\ 0 \quad others \end{cases} \tag{27}$$

For convenience, denote price-quantity set of market supply function as

$\Omega_t = \left(\omega^{(S)}\left(\mu_t\right), \rho_w^{(S)}\left(\mu_t\right)\right)^T$, where

$$\omega^{(S)}\left(\mu_t\right) = \left[\sum_{I\in\mu_t}\sum_{k_I=1}^{K_I}\sum_{v=1}^{3}\min\omega_{\left(I_{k_I},v\right)}, \sum_{I\in\mu_t}\sum_{k_I=1}^{K_I}\sum_{v=1}^{3}\max\omega_{\left(I_{k_I},v\right)}\right] and\ \ \rho_w^{(S)}\left(\mu_t\right) = \left[\rho_w^{(\mu_t)}, \overline{\rho_w}\right]; 1\le t\le 3I^*; \rho_w^{(\mu_0)} = \varnothing; I=1,\ldots,I^*; k_I=1,\ldots,K_I$$

Obviously, $\Omega_t = \varnothing \Leftrightarrow \left[\omega^{(S)}\left(\mu_t\right) = \varnothing\right] \cup \left[\rho_w^{(S)}\left(\mu_t\right) = \varnothing\right]$.

Let supply equal to demand, equilibrium in wholesale market is reached. Solution to market clearing quantity $W^{(*)}$ and MCP price $\rho_w^{(*)}$ is given by Eq. 28. To incentivize generator to control CO_2 intensity, self-consumed electricity rate and fuel cost per MWh, ISO chooses equilibrium price set (EPS) lower-bound as MCP price. As seen in Eq. 29, EPS is identified as on W-ρ_w plane, the price interval where line $W^{(*)}$ (or its immediate-up quantity set) first passes through cuts the next higher price interval.

$$W^{(*)} = W^{(D)}.(1+s) \in \omega^{(S)}\left(\mu_{t^*}\right) \cup \left(\max\omega^{(S)}\left(\mu_{\left(t^*-1\right)}\right), \min\omega^{(S)}\left(\mu_{t^*}\right)\right) and\ \ \rho_w^{(*)} = \min\left(\rho_w^{(S)}\left(\mu_{t^*}\right)\right) \tag{28}$$

where,

$$t^* = \left\{\min(t) \middle| \sum_{I\in\mu_t}\sum_{k_I=1}^{K_I}\sum_{v=1}^{3}\min\omega_{\left(I_{k_I},v\right)} \le W^{(D)}.(1+s) \le \sum_{I\in\mu_t}\sum_{k_I=1}^{K_I}\sum_{v=1}^{3}\max\omega_{\left(I_{k_I},v\right)}\right\} \cup \left\{t \middle| W^{(D)}.(1+s) \notin \omega^{(S)}\left(\mu_t\right), and \sum_{I\in\mu_{(t-1)}}\sum_{k_I=1}^{K_I}\sum_{v=1}^{3}\max\omega_{\left(I_{k_I},v\right)} < W^{(D)}.(1+s) < \sum_{I\in\mu_t}\sum_{k_I=1}^{K_I}\sum_{v=1}^{3}\min\omega_{\left(I_{k_I},v\right)}\right\}$$

Equilibrium price-quantity set (EPQS) and EPS can be written as

$$\Omega_{t^{**}} = \left(\omega^{(S)}\left(\mu_{t^*}\right), \rho_w^{(S)}\left(\mu_{t^*}\right) \backslash \bigcup_{\gamma=t^*+1}^{3I^*} \rho_w^{(S)}\left(\mu_\gamma\right)\right)^T \tag{29}$$

Obviously, $\Omega_{t^{**}} \neq \varnothing$.

When dispatching electricity ISO laid the rule as, prior dispatch bid electricity of generators having bid quantity where price is lower than EPS lower-bound, thereafter average dispatch the spare electricity among generators having bid quantity at EPS lower-bound price. Also, this EPS dispatch rule has positive policy effects on resources allocation and CO_2 mitigation.

5. Simulation

5.1. Data Process

This section provides a numerical simulation to give an intuitive version on validity of the proposed CO_2 saving dispatch model. Assume there are 8 generators in wholesale competitive market and respective operational information is given below. Table 1 is fuel consumption function (ton/hour). Table 2 is upper- and lower-bound active power (MW), CO_2 emission intensity (ton/MWh), coal price (CNY/ton) as well as self-consumed electricity rate.

Table 1. *Fuel consumption function of each generator.*

Generator	**Constant**	**Linear coefficient**	**Quadratic coefficient**
1	8.0	0.1	0.001
2	6.5	0.1	0.002
3	6.0	0.1	0.002
4	3.0	0.3	0.001
5	3.5	0.3	0.001
6	1.0	0.6	0.0015
7	1.0	0.6	0.01
8	2.0	0.8	0.02

Table 2. *Technical constraint, CO_2 emission intensity, self-consumed electricity rate and coal price of each generator.*

Generator	**upper-bound power**	**lower-bound power**	**CO_2 intensity**	**Self-consumed rate**	**Coal price**
1	300	100	0.3	0.04	200
2	200	80	0.5	0.05	250
3	200	80	0.6	0.05	300
4	100	40	0.7	0.06	300
5	100	40	0.75	0.06	350
6	50	20	0.8	0.06	350
7	50	20	0.9	0.08	500
8	50	20	1.0	0.09	600

Regulatory information released by electricity regulator is given below, predicted load demand is 3.0×10^6 MWh, grid line loss rate is 0.06, electricity price range is 200-400 CNY/MWh, and market share is no higher than 0.3. Based on electricity regulatory information, environment regulator releases the following information, supplied allowances is 1590 kiloton, carbon price range is 10-50 CNY/ton, yardstick CO_2 intensity is 0.5 ton/MWh, default emission penalty rate is 0.2, and CO_2 submarket transaction charge rate is 0.1.

5.2. Results and Discussion

Figure 2 is generator's demand curve in carbon market. Since marginal emission revenue of start-generation (MERS) is negative for generator 7 and 8, their bid CO_2 allowances is zero. For other generators 1-6, respective bid allowances is 297.6, 500.9, 601.0, 707.9, 758.4 and 809.0 kiloton, correspondingly their bid price upper-bound is 13.33 CNY/tCO_2 for generator 6 and 50 CNY/tCO_2 for generators 1-5. The result verified allocation efficiency in carbon market auction: generator featured as low CO_2 intensity is not only willing to bid higher price but also willing to bid lower allowances, if keeping other things the same. Furthermore, total bid allowances is 3674.8 kiloton, almost double to environment regulator issued allowances, which means aggressive competition in carbon market. Of course it will bring about direct CO_2 saving effect.

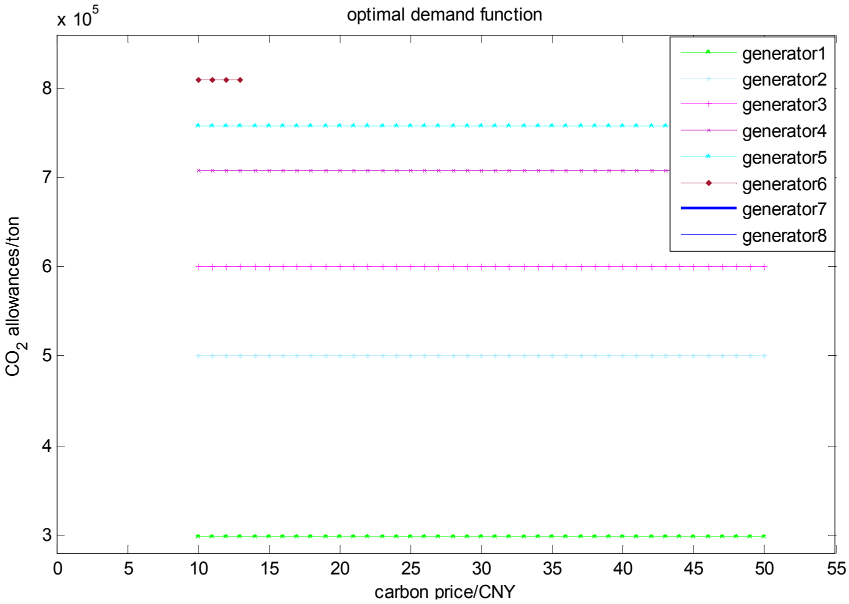

Figure 2. *Demand curve of generators in carbon market.*

Figure 3 displays ECPR interval is 13.33-50 CNY/tCO_2. In line with ECPR pricing and allocation rule, MCP is 50 CNY/tCO_2 and equilibrium allowances is 1590.0 kiloton. Concerning Figure 2 and 3, generators 1-6 respective allocated CO_2 allowances is 297.6, 323.1, 323.1, 323.1, 323.1 and 0 kiloton. Specifically, generator 1 gets maximum quantity determined by market share regulation and generators 2-5 allocate the spare allowances on average. Because of relative low MERS, generator 6 allocated allowances is 0.

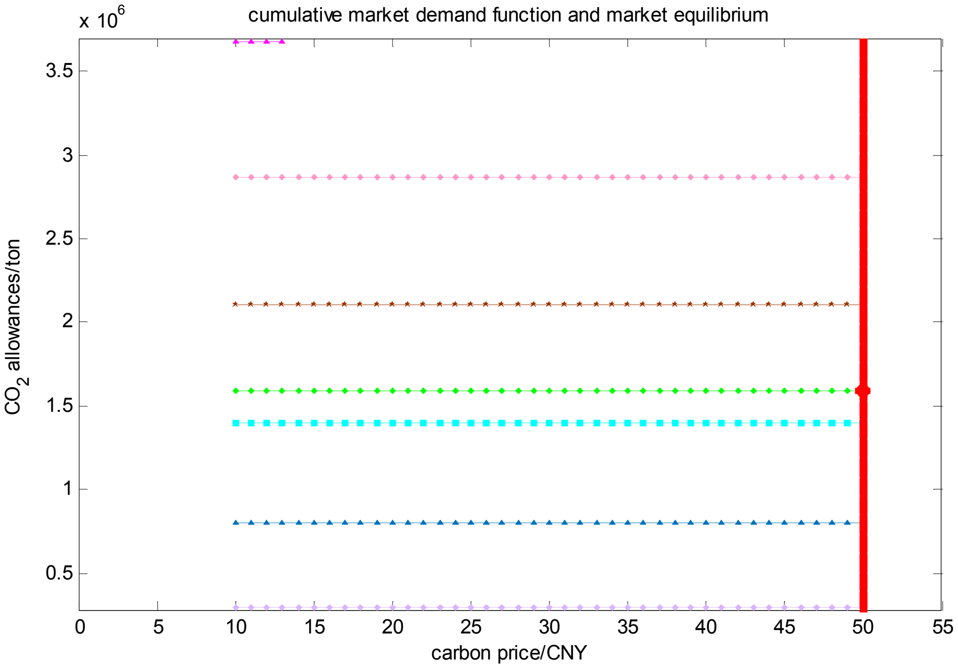

Figure 3. *Carbon market demand function and equilibrium.*

Figure 4 reports possible sold electricity of generators determined by carbon market equilibrium. Concretely, generator 1 reaches market share regulation, generators 2-5 are under market share restriction because allocated CO_2 allowances are lower than their bid quantities, and generators 7-8 have no possible sold electricity because of negative MERS. Although generator 6 has positive bid CO_2 allowances, however relative lower MERS than generators 1-5 causes zero allocated allowances, hence also has no possible sold electricity.

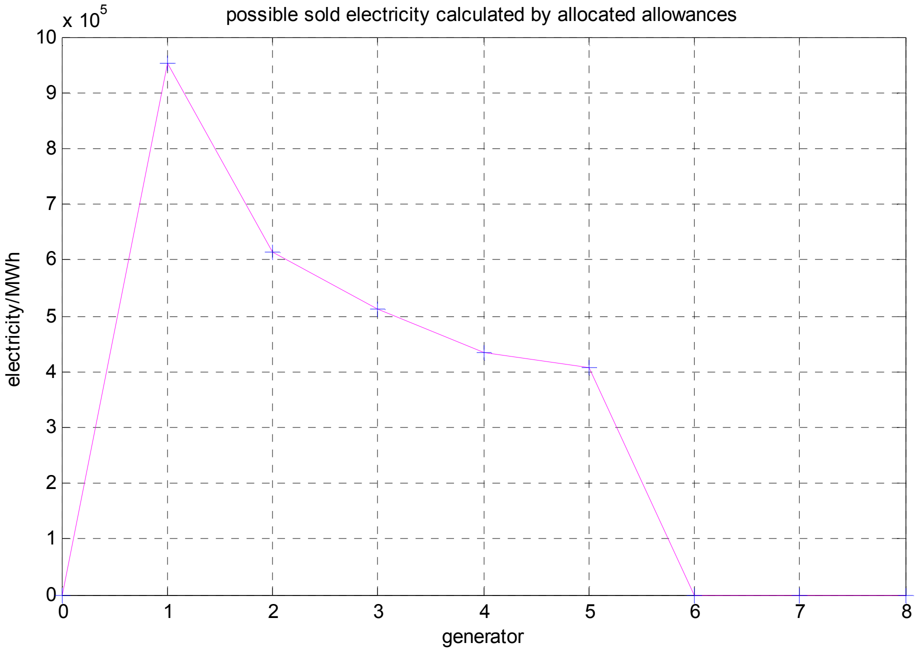

Figure 4. *Possible sold electricity of each generator calculated by allocated allowances.*

In wholesale market auction, generator's optimal supply function is given below.

At price-quantity set $(\omega_{j1}, \kappa_{j1})$, individual optimal supply function is

$$W_1 = 954000 \quad \rho_{w1} \in [200,400]; \; W_2 = 954000 \quad \rho_{w2} \in [200,400]; \; W_3 = 909780 \quad \rho_{w3} \in [211.9,400];$$
$$W_4 = 584910 \quad \rho_{w4} \in [200,400]; \; W_5 = 566040 \quad \rho_{w5} \in [230.8,400]$$

At price-quantity set $(\omega_{j2}, \kappa_{j2})$, it is

$$W_1 \in [0,954000] \quad \rho_{w1} \in [200,400]; \; W_2 \in [0,954000] \quad \rho_{w2} \in [200,400]; \; W_3 \in [0,954000] \quad \rho_{w3} \in [222.9,400];$$
$$W_4 \in [0,584910] \quad \rho_{w4} \in [200,400]; \; W_5 \in [0,566040] \quad \rho_{w5} \in [244.7,400]; \; W_6 \in [0,268870] \quad \rho_{w6} \in [302.7,400]$$

At price-quantity set $(\omega_{j3}, \kappa_{j3})$, it is

$$W_1 \in [0,954000] \quad \rho_{w1} \in [200,400]; \; W_2 \in [0,954000] \quad \rho_{w2} \in [209.3,400]; \; W_3 \in [0,954000] \quad \rho_{w3} \in [244.8,400];$$
$$W_4 \in [0,584910] \quad \rho_{w4} \in [225.8,400]; \; W_5 \in [0,566040] \quad \rho_{w5} \in [272.4,400]; \; W_6 \in [0,268870] \quad \rho_{w6} \in [332.2,400]$$

Concretely, generators having bid electricity at all three sets their MPCS is upward ordered as generators 1, 2, 4, 3 and 5 in each set, which is in accordance with the order of respective bid price lower-bound in corresponding set. This result verified that wholesale market auction may prompt economic dispatch and resources allocation efficiency. Concerning bid quantity, generators 1-3 get market share restriction and generators 4-6 reach respective active power constraint. Because of either bid electricity set or bid price set is empty, generators 7-8 have no optimal supply curve in all price-quantity sets. This result also proved no physical withholding and high efficiency of the proposed dispatch model.

Figure 5 provides wholesale market supply function and equilibrium. The EPQS set, MCP price and dispatched electricity are $\Omega_{t^{**}} = \{222.928 \le \rho_w \le 225.7696; 2492900 \le W \le 3446900\}$, 222.928 CNY/MWh and 3180000 MWh, respectively. In line with EPS dispatch rule, generators 1-4 each allocated load is 954000, 954000, 687090 and 584910 MWh, other generators have no allocated load. In equilibrium generators 1-2 get market share restriction, generator 4 is at active power constraint, only generator 3 is under its maximum generation state.

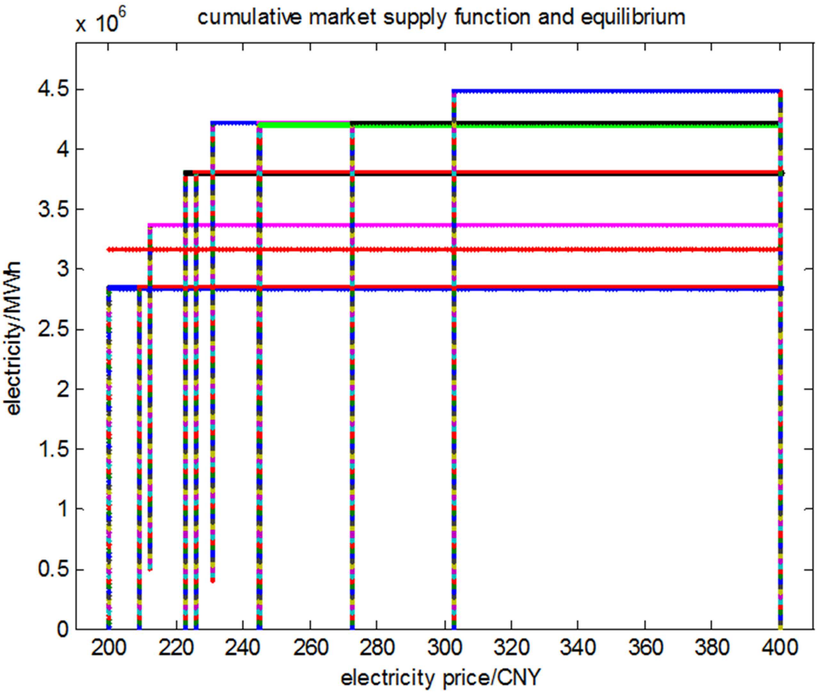

Figure 5. *Wholesale market supply function and equilibrium.*

In CO_2 submarket, generators 2-4 will purchase allowances from other generators at an expected price 63.25 CNY/ton or direct purchase allowances from environment regulator at 66.0 CNY/ton. Generator 5 will sell surplus allowances at an expected price 27.5 CNY/ton. It verified that generator's best policy in carbon market auction is evaluating CO_2 allowances for self-use, not speculation. Comparing with other dispatch models, allocating CO_2 allowances on average will emit 2047.0 kiloton CO_2, allocating dispatched load on average will emit 2350.8 kiloton CO_2, however the proposed dispatch model just emits

1665.4 kiloton CO_2, meaning that 22.91% or 41.16% emissions is avoided. Therefore the CO_2 saving dispatch model can utilize both carbon market and wholesale market to optimize resources allocation, to incentivize generator controlling emission intensity and improving operational advantage, as a consequence brings about CO_2 mitigation effect.

6. Conclusions

Deep CO_2 mitigation provides a challenge to electricity sector during liberalized market process. To incentivize generator to carry out CO_2 mitigation through market mechanism, this article proposed an optimal CO_2 saving dispatch model for wholesale market under consideration of emissions trade. It works as a dynamic process of, (i) electricity and environment regulators coordinately issue regulatory information; (ii) initial CO_2 allowances allocation through carbon market auction; (iii) electricity transaction through wholesale market auction; and (iv) CO_2 allowances submarket transaction. This model couples carbon market with electricity market and utilizes price-quantity uncorrelated combinatorial auction to organize both CO_2 allowances and electric energy trade. By setting rigorous rule on CO_2 submarket transaction, it may avoid allowances speculation as well as windfall profits problem.

When making decision in both carbon market and electricity market generator needs to evaluate the profitability of CO_2 allowances, which means at each stage it needs to concern possible transaction in CO_2 submarket. This article builds two stochastic math programmings to depict generator's decision at each stage, which provides its bid curve for CO_2 allowances in carbon market and for selling electricity in wholesale market. Through adding up individual demand curve (supply curve) and matching with total allowances supplied (load demanded), market equilibrium is reached.

In carbon market bid price upper-bound (reserve price) of generators is ordered according to their operational advantage. The same is also true for allocated CO_2 allowances of each generator. These features have a benefit to improve market efficiency, as a consequence bring about direct CO_2 abatement effect. Likewise, in wholesale market bid price lower-bound (reserve price) is ordered in line with generators' operational advantage, meanwhile their bid electricity upper-bound gets respective capacity constraint or market share regulation. These features imply that the proposed CO_2 saving dispatch model can prompt economic dispatch, enhance resources allocation efficiency, consequently cause indirect CO_2 abatement effect. Numerical simulations also verified the effectiveness of this CO_2 saving dispatch model.

Nomenclature

π_j : expected profit of generator in carbon market and wholesale electricity market, unit: CNY ;

$W^{(D)}$: grid load demand, unit: MWh ;

$F_j(P_j)$: fuel consumption function. Theoretically, it has a characteristic of $\frac{dF_j(P_j)}{dP_j} > 0$ *and* $\frac{d^2F_j(P_j)}{d^2P_j} > 0$. This article sets its concrete form as a quadratic function, unit: $ton/hour$;

$\rho_{ej}, \rho_{ej}^*, \rho_e^*, \overline{\rho_e}, \underline{\rho_e}$: bid price, marginal emission revenue of start-generation, market clearing price, price lower- and upper-bound of CO_2 allowances in carbon market, unit: CNY/ton ;

$\rho_{wj}, \rho_{wj}^*, \rho_w^*, \overline{\rho_w}, \underline{\rho_w}$: bid price, marginal power cost of start-generation, market clearing price, price lower- and upper-bound of electricity in wholesale market, unit: CNY/MWh ;

ρ_{cj} : coal price, unit: CNY/ton ;

$E_j, E_j^*, E^{(S)}$: bid CO_2 allowances, winner allocated allowances, and allowances cap, unit: ton ;

e_j, e : emission intensity, yardstick emission intensity, unit: ton/MWh ;

$P_j, \underline{P_j}, P_j^{(N)}$: active power, lower-bound active power, and nameplate (i.e. upper-bound) active power, unit: MW ;

$W_j, W_j^*, W_j^{(Self)}, W^{(Loss)}$: bid load, winner allocated load, self-consumed electricity and grid line loss, unit: MWh ;

T_j : yearly maintenance time and non-planned outage time of generation facility, unit: $hour$;

τ : market share allowed by regulator;

m_j : emission intensity slack factor, definitely $e_j\left(1+m_j\right) \equiv e$;

α, β : CO_2 default emission penalty rate, submarket transaction charge rate, generally, $0 < \alpha, \beta \le 1$;

s_j, s : self-consumed electricity rate, grid line loss rate, definitely $s_j \equiv \frac{W_j^{(Self)}}{W_j}$ and $s \equiv \frac{W^{(Loss)}}{W^{(D)}}$.

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