International Journal of Economy, Energy and Environment
2016; 1(1): 1-7
Published online October 20, 2015 (http://www.sciencepublishinggroup.com/j/ijeee)
doi: 10.11648/j.ijeee.20160101.11

Emission Market Design Based on Supply Function Equilibrium Model

Shijun Fu

Department of Logistic Engineering, Chongqing University of Arts and Sciences, Chongqing, China

Email address:
fsjphd@yahoo.com

To cite this article:
Shijun Fu. Emission Market Design Based on Supply Function Equilibrium Model. *International Journal of Economy, Energy and Environment*. Vol. 1, No. 1, 2016, pp. 1-7. doi: 10.11648/j.ijeee.20160101.11

Received: September 25, 2015; **Accepted**: October 21, 2015; **Published**: August 28, 2016

Abstract: This paper designs an emission market for electricity industry based on supply function equilibrium model. It refers to major features of the existing emission market. And it is improved in (i) electricity-environment coordinated regulation, (ii) adopting the first price-quantity sealed auction for allowances allocation, (iii) penalty covering generator's all emissions, and (iv) pricing allowances through both market bidding process and regulatory process coordinately. We depict generator's decision as a stochastic parameter linear programming model, which provides us its bidding curve. According to market equilibrium, each generator gets its allowances at a market clearing price. We find that, (i) the new market can not only effectively motivate generator to mitigate emission individually, but also can save allowances through market process; (ii) it can be an effective instrument to pricing emission. Finally, we present a numerical simulation for its validity, and results are well fitted to the theoretical conclusions.

Keywords: Electricity Industry, Emission Market Design, Supply Function Equilibrium, Complexity System Modeling

1. Introduction

At the end of 2007, the UNFCCC (United Nations Framework Convention on Climate Change) passed the Bali Roadmap in Indonesia. Since then, the low carbon economy has developed quickly. Year 2009 saw the UNFCCC passed the Copenhagen accord. And this further advanced the low carbon economy development.

Emission market, known as cap-and-trade system, has been adopted by regions and countries such as EU ETS (European Union Emission Trading Scheme), NSW ETS (New South Wales Emission Trading Scheme), and RGGI (Regional Greenhouse Gas Initiative). In these systems, an authority sets a cap on the total amount of emission allowances, and allocates them to appropriate firms free of charge (in the past a few portion is allocated by auction). In order to minimize the costs caused by emission cap regulation, the authority allows emission allowances to be traded among firms [1].

As the main source of industry discharged GHG (Greenhouse Gas), emission market needs to be harmonized with electric power industry development. And the current emission market has some shortcomings in this aspect. Reference [2] found that TGCs (tradable green certificates) of EU (European Union) countries had different market conditions, and this had damped the development of EU electricity market. Reference [3] also found that different emission abatement policies might conflict each other, and would decrease mitigation effectiveness. It is profound to effectively motivate generator mitigating emission on condition of electric power satisfying the national economy development [2]. So the electric power industry not only needs regulated electricity market, but also needs regulated emission market. More generally, it needs the two markets regulated coordinately [4].

The current emission market pricing mechanism has little incentive that motivates generator to design and build cleaner and more efficient production units. Reference [5] proved that pricing allowances through market process might decrease generator's mitigation investment because of market externality. In the first pilot period 2005-2007, EU ETS induced emission price fluctuating vigorously, which was the main problem of the mechanism [1]. Reference [6] proved that price vibrating too much could not effectively motivate generator's mitigation investment. Reference [7] also gave an empirical evidence that EU ETS could not support emission price high enough to encourage generator mitigation.

In emission market, the initial allowances allocation is indeed the crucial parameter that ensures the emission cap to be realized and generator to be motivated investing in mitigation. But the current grandfathering and NAP (national allocation plans) has some difficulties to achieve this objective. Reference [8] applied NAP based on EU ETS framework to forecast emission price, and found that allowances supply abundance was the main reason why price decreased in the first pilot period of EU ETS. Because of initial allocation free of charge, generator gets substantial windfall profits by trading allowances and passing costs to the end consumers. This is strongly supported by Sijm's evidence based on an empirical analysis of power generation profitability in the context of EU ETS [9]. Obviously, allowances supply abundance and windfall profits unlikely effective motivate generator to invest in CCS (Carbon Capture and Sequestration) and other mitigation technology.

Despite frequent articles in the popular press and numerous speculative debates in specialized magazines, the scientific literature on how to design an efficient market for the emission abatement complexity system is relatively limited. Reference [10] proposed a static model for a perfect market with emission certificates. This work held that there was a minimum cost equilibrium for companies facing a given emission allowances cap. Reference [11] studied the policy effectiveness of price-based instruments and quantity-based instruments. This work aimed to solve how to manage emission abatement risk induced by emission market process. Reference [12] formed a linear programming model to forecast eastern European countries' emission price and policy effectiveness on motivating generator to use renewable energy. This model considered restrictions of load balance, generator's capacity, coal-fired consumption, total allowances, time value of capital, and technology advance. Based on LB (load-based) scheme, literature [13] proposed an unbundled GEAC (generation emission attribute certificates) to motivate generator to adopt abatement policies. This mechanism considered factors of emission rate of an individual certificate, default emission rate, grid line loss rate, which could promote generator to internalize emission price signal at the dispatch level and be compatible with electricity market. Reference [14] constructed a cost minimizing integer linear programming model which included restrictions of load balance, active power, coal-fired consumption, and total allowances. They found that EU ETS could improve competitive ability of those generators who owned low emission intensity.

In order to effectively motivate generator to mitigate emission on condition of electric power satisfying the national economy development, based on the work of [12-15], this paper develops a new emission market for allowances allocation. It refers to major features of existing emission market, such as regulation, cap-and-trade, penalty, and period. And it is improved in, (i) electricity-environment coordinated regulation, (ii) adopting the first price-quantity sealed auction for allowances allocation, (iii) penalty covering generator's all emissions, and (iv) pricing allowances by market bidding process and regulatory process harmonically. As we will see, the new market not only can effectively motivate generator to mitigate emission individually, but also can save allowances through market process.

This paper is organized as follows: Section 2 depicts hypothesis, variable selection and the new emission market framework. Section 3 analyzes generator's bidding decision in the new market. Section 4 gives an equilibrium analysis. Section 5 makes a discussion and forms a way to test the new market's validity. Section 6 provides a numerical simulation. Finally, a brief conclusion is given in section 7.

2. Market Description

2.1. Hypothesis

For simplifying our theoretical work, and focusing on the essence of the new emission market, we set the following hypotheses:

- the emission market is special for coal-fired power plants (generators), and all load demand is satisfied by coal-fired power plants.
- there has n generators, each generator owns only one set of generating facility.
- electricity market is a wholesale competitive market, and the total generating capacity is more than peak load of the electric power system.
- do not consider grid technique restrictions, such as power flow distribution, and electric ancillary service market, reactive power transaction, and black start.
- each generator's emission intensity is above zero.

2.2. Variables Selection

In the new emission market, effectively motivating generator to mitigate emission on condition of electric power satisfying the national economy development is its essence. In order to describe the new market clearly and analyze generator's decision making behavior exactly, we need to define the following variables:

π_j : generator's expected profit $(j = 1, ..., n)$;

$W^{(D)}$: electric power system forecasted load;

$F_j(P_j)$: generator's coal-fired consumption function. Generally, it is a convex and increase function. In this paper, we adopt $F_j(P_j) = a_j + b_j.P_j + c_j.P_j^2$;

$\rho_{ej}, \rho_{ej}^*, \rho_e^*, \rho_w, \rho_{cj}$: generator's bidding price, start-generate marginal emission revenue and market equilibrium price; electricity price; coal price. Variables under-lined (up-lined) are their lower-limit (upper-limit);

$E_j, E^{(S)}; e_j, e$: generator's bidding allowances, total allowances; generator's emission intensity, standard emission intensity. The later is defined as $e \equiv E^{(S)} / (W^{(D)}(1+s))$;

$P_j, \underline{P_j}, P_j^{(N)}$: generator's operation active power, lower-limit operation active power, upper-limit active power;

τ : allowed market power rate;

m_j : generator's emission intensity slack factor, it is defined as $e_j\left(1+m_j\right)\equiv e$. In the new market, it has two functions: motivating (punishing) generator to decrease (increase) emission intensity and ensuring power system's safety at the cost of emissions increased appropriately.

α, β : emission price penalty factor and second transaction fee rate, generally, $0<\alpha,\beta\leq 1$.

2.3. New Emission Market's Framework

In order to overcome the existing emission market's shortcomings described in section 1, and effectively motivate generator mitigating emission on condition of electric power satisfying the national economy development, we develop a new emission market for allowances allocation.

As described in Fig. 1, firstly, the new market operating begins with electricity regulator releasing electricity regulation information. These include yearly forecasted load demand, electricity price scope, allowed market power rate, and grid synthetic line loss rate. In fact, these are requirements of economy development, electricity market's health and stability operating, and electric power system technique constraint. And emission market satisfying these requirements may benefit electricity-environment coordinated development.

Secondly, based on electricity regulatory information, environment regulator releases environmental regulatory information. These include standard emission intensity factor, total allowances, upper and lower emission price, emission price penalty factor, and emission second transaction fee rate.

According to Fig. 1, we note that e does not include those emissions induced by generator's self-consumed electricity. However, generator's emission intensity factor e_j is calculated by its sold and self-consumed electricity. If $e_j > \mathrm{e}$, then all its emissions will be charged with extra α. This mechanism can motivate generator to improve operation management and invest in CCS.

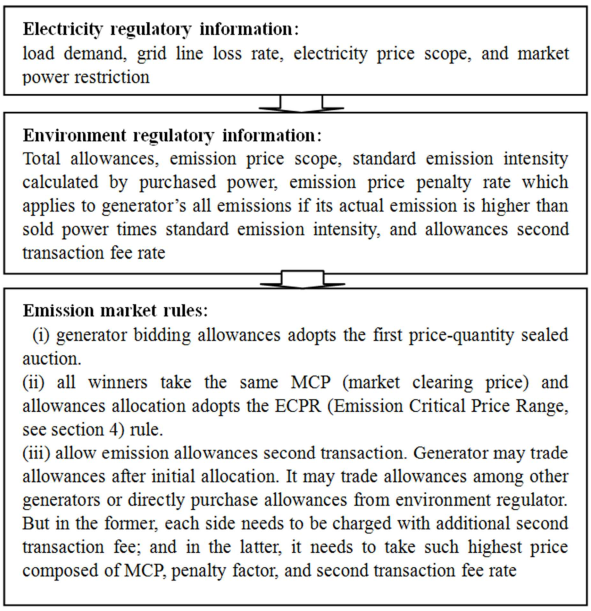

Figure 1. *The new emission market's framework.*

Setting emission price scope has a benefit to overcome price fluctuating too much and increase market stability.

The new emission market allows allowances second transaction. Generator may trade emission allowances in the latter when making electricity market decision. It may trade allowances among other generators or directly purchase allowances from environment regulator. But in the former, each side needs to be charged with extra β; and in the latter, it needs to take such highest price composed of MCP, α, and β. This is because electric power industry's primary task is to satisfy national economy development. In order to realize electricity-environment coordinated development, sometimes, we need to ensure load at a cost of emission increased appropriately. But in this case, we must punish those generators whose emission intensity is too high.

3. Generator's Decision Making Behavior

3.1. Decision Model

In the new market, generator faces a challenge to determine its bidding curve. We refer to supply function equilibrium methodology [16], and construct a stochastic parameter linear programming for generator's bidding decision.

According to Fig. 1, generator bidding allowances and price depends on (i) allowances bided can produce potential revenue and induce potential coal cost, (ii) allowances cost, and (iii) default emission penalty induced by its high emission intensity. Because generator can not get exact information of electricity price and operating active power (see hypothesis three), it may assume them as uniform distribution stochastic variable in their allowed range. Furthermore, generator can not know other generators' cost information (i.e., coal price, emission intensity, coal-fired consumption function, see hypothesis four and five), its bidding decision can only depend on those public information and its own private information. In the allowances second transaction period, generator selling surplus allowances will not only be charged with extra β, but also may be unrealizable; and it purchasing shortage allowances will take such price higher than the MCP despite from other generators or from environment regulator.

In lieu with the above analysis, taking hypothesis one, two, four, and five into consideration, generator's decision model can be described as:

$$\begin{aligned}\max \pi_j &= E_j/(e_j(1+s_j))\int_{\underline{\rho_w}}^{\overline{\rho_w}}\rho_w\phi(\rho_w)d\rho_w - E_j\rho_{ej}\\ &-\int_{\underline{P_j}}^{P_j^{(N)}}[(a_j+b_j.P_j+c_jP_j^2)E_j\rho_{ej}/(e_jP_j)]\phi(P_j)dP_j\\ &+\min\left(0,m_j\right)E_j\alpha\rho_{ej}.\end{aligned} \tag{1}$$

$$\text{St. } E_j/(e_j(1+s_j))\leq \tau E^{(S)}/e. \tag{2}$$

$$e_j\left(1+m_j\right)=e. \quad (3)$$

$$\underline{P_j} \le P_j \le P_j^{(N)}. \quad (4)$$

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

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

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

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

3.2. Optimal Demand Function

Solving the above model, and ordering generator's marginal profit of emission being nonnegative, the optimizing bid price is,

$$\begin{aligned}\rho_{ej} \le [[(\underline{\rho_w}+\overline{\rho_w})/(2e_j(1+s_j)e_j(P_j^{(N)}-\underline{P_j}))]-\rho_{ej}[a_j In(P_j^{(N)}/\underline{P_j})+\\ b_j(P_j^{(N)}-\underline{P_j})+c_j((P_j^{(N)})^2-(\underline{P_j})^2)/2]]/(1-\min(0,e/e_j-1)\alpha)e_j(P_j^{(N)}-\underline{P_j}).\end{aligned} \quad (9)$$

We call (9)'s right side as generator's start-generate marginal emission revenue ρ_{ej}^*. Under the optimal bid price restriction, generator's optimizing allowances is equal to its upper-limit, and vice versa. And considering restriction (8), the generator's optimal demand function can be given as,

$$E_j=\tau E^{(S)}e_j(1+s_j)/e; \underline{\rho_e} \le \rho_{ej} \le \min(\overline{\rho_e}, \rho_{ej}^*). \quad (10)$$

4. Market Equilibrium and Allowances Allocation

4.1. Market Demand Function

In order to get market demand function, we need to separate n generators into m sets according to identical ρ_{ej}^*, and define an index function as,

$$i=i_{k_i}=\left\{\left(i,k_i\right)\middle|\begin{matrix}i=1,2,...,m; k_i=1,2,...,K_i; \rho_{e,i_1}^*=...=\rho_{e,i_{k_i}}^*=...=\rho_{e,i_{K_i}}^*\\ \forall\rho_{e,i}^*\ne\rho_{e,r}^*; r\ne i; 1\le r,i\le m; 1\le m,K_i\le n\end{matrix}\right\}. \quad (11)$$

where K_i is generator number in the i-th set. Assume the m sets are ordered as $\rho_{e1}^*>\rho_{e2}^*>...>\rho_{ei^*}^*>...>\rho_{em}^*$, where $1\le i^*\le m$. And the i-th $(i\le i^*)$ set has a positive bidding quantity, and vice versa.

The environment regulator adds up all sealed bidding curves and forms the market demand curve. It is given as,

$$E^{(D)}\left(\rho_e\right)=\begin{cases}\sum_{i=1}^{i^*}\sum_{k_i=1}^{K_i}E_{i_{k_i}}, if \underline{\rho_e}\le\rho_e\le\min\left(\overline{\rho_e},\rho_{e,i^*}^*\right).\\ \cdots\\ \sum_{i}\sum_{k_i=1}^{K_i}E_{i_{k_i}}, if \underline{\rho_e}\le\rho_e\le\min\left(\overline{\rho_e},\rho_{e,i}^*\right), 1\le i\le i^*.\\ \cdots\\ \sum_{k_1=1}^{K_1}E_{1_{k_1}}, if \underline{\rho_e}\le\rho_e\le\min\left(\overline{\rho_e},\rho_{e,1}^*\right).\\ 0, \quad others\end{cases} \quad (12)$$

4.2. Market Supply Function and Equilibrium

As Fig. 1 described, the market supply function is given by environment regulator, which is at most completely inelasticity. By putting market demand curve and supply curve together, we can get the market equilibrium $E^{(*)}$, and realize pricing emission allowances.

In order to effectively motivate generator mitigating emission, it is necessary to take ECPR's (emission critical price range) upper-limit as MCP. The ECPR is defined as, (i) the covered price range that demand line identities to line $E^{(*)}$, or (ii) the covered price range by line $E^{(*)}$'s immediate-up demand line on the $E-\rho_e$ plane.

The emission allowances pricing formula is given by,

$$\rho_e^*=\begin{cases}\min(\overline{\rho_e},\rho_{e,i^{**}}^*).\\ if \quad E^{(*)}=E^{(S)}; 1\le i^{**}\le i^*; \sum_{i=1}^{i^{**}-1}\sum_{k_i=1}^{K_i}E_{i_{k_i}}<E^{(*)}\le\sum_{i=1}^{i^{**}}\sum_{k_i=1}^{K_i}E_{i_{k_i}}.\\ \min(\overline{\rho_e},\rho_{e,i^*}^*); if \quad E^{(*)}=\sum_{i=1}^{i^*}\sum_{k_i=1}^{K_i}E_{i_{k_i}}.\end{cases} \quad (13)$$

This MCP is the harmonized result of market bidding process and electricity-environment coordinated regulatory process. Obviously, the lower emission intensity, the more competitive advantages generator owns. So ECPR upper-limit pricing mechanism not only can ensure emission price not vibrating too much, but also can provide an incentive to generator mitigating emission.

4.3. Allowances Allocation

When environment regulator allocates equilibrium quantity among those generators who win auction in the market biding process, it sets the allocation rule as, (i) to completely satisfy those generators who still have bidding quantity where price is higher than the ECPR's upper-limit; (ii) to averagely allocate the reserved quantity among those generators who have bidding quantity at the ECPR, but have no bidding quantity where price is higher than the ECPR's upper-limit. We call it as ECPR allocation rule. Generally, those who bid higher price than upper-limit have more competitive advantages. So this rule can encourage generator to mitigate emission.

5. Discussions

In order to test the new market's validity, we compare it with the current free allocation mechanism. Considering allowances is allocated averagely free of charge, we can calculate total supplied electricity under the restriction of emission cap. Then the saved allowances under the new market can be described as,

$$\Delta E = E^{(\mathrm{S})} + [(W^{(D)}(1+s)) - E^{(\mathrm{S})}\sum_{j=1}^{n} 1/(ne_j(1+s_j))] / \sum_{j=1}^{n} 1/(ne_j(1+s_j)) - \mathrm{E}^{(*)}. \quad (14)$$

6. Simulation

6.1. Data

In this section we present a numerical simulation to show how the new market works well. Assume electricity market has 4 generators, and their operation information is given by Table 1 and 2. The former is generator's coal-fired consumption function (*tonne/hour*), and the latter is generator's upper-limit active power (*MW*), lower-limit active power (*MW*), CO2 emission intensity (*tonne/MW.h*), coal price (*Yuan/tonne*), and self consumed electricity rate.

Table 1. *Coal-fired consumption function.*

Generator	Constant	Linear coefficient	Square coefficient
G1	6.0	0.1	0.002
G2	3.5	0.3	0.001
G3	1.0	0.6	0.01
G4	2.0	0.8	0.01

Table 2. *Technical restrictions, CO2 emission intensity, self-consumption rate, and coal price.*

	Upper	Lower	Intensity	Self-consumption	Coal price
G1	200	80	0.3	0.04	150
G2	100	40	0.8	0.06	150
G3	50	20	0.5	0.08	190
G4	50	20	0.9	0.10	200

Electricity regulator promulgates information as follow, forecasted load demand and grid line loss is 1600000 (*MW.h*), electricity price is between 200 and 300 (*Yuan/MW.h*), and market power rate is less than 0.4.

Based on electricity regulatory information, environment regulator promulgates information as below, supplied allowances is 800000 (*tonne*), emission price is between 10 and 50 (*Yuan/tonne*), standard emission intensity is 0.5 (*tonne/MW.h*), emission price penalty factor is 0.2, and allowances second transaction fee rate is 0.1.

6.2. Results

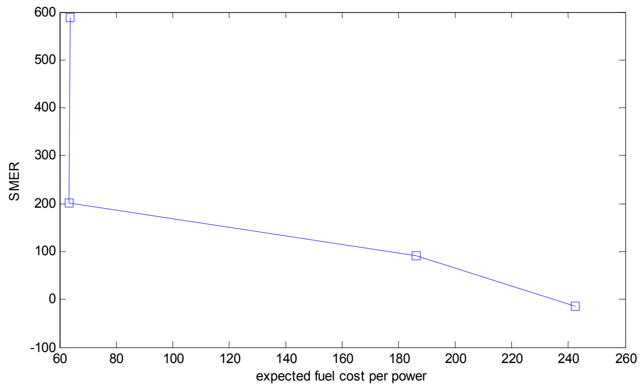

Figure 2. *Relationship between start-generate marginal emission revenue and expected fuel cost per generated power.*

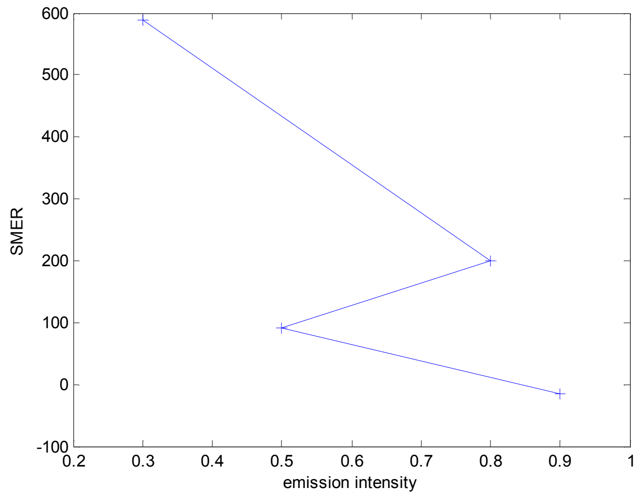

Figure 3. *Relationship between start-generate marginal emission revenue and generator's emission intensity.*

Fig. 2 provides the relationship between ρ_{ej}^{*} and expected fuel cost per generated power. And Fig. 3 is the relationship between ρ_{ej}^{*} and generator's emission intensity. The two figures show that, generally, ρ_{ej}^{*} has a negative relationship to both expected fuel cost per generated power and emission intensity (except $e_j = e$). So ρ_{ej}^{*} can indeed reflect generator's operation advantages, and generator's bidding price based on this information may induce allowances allocation efficiency.

Each generator's bidding curve is given by equation (15) to (18), and ECPR is between 10 and 50 (*Yuan/tonne*).

$$E_1 = 199680, 10 \le \rho_{e1} \le 50. \quad (15)$$

$$E_2 = 542720, 10 \le \rho_{e2} \le 50. \quad (16)$$

$$E_3 = 345600, 10 \le \rho_{e3} \le 50. \quad (17)$$

$$E_4 = 0. \quad (18)$$

Although generator 4 requires 633600 (*tonne*) allowances, its ρ_{ej}^{*} is too low, so its bidding curve is zero.

Fig. 4 reveals the market equilibrium. As we can see, the equilibrium allowances is 800000 (*tonne*), and considering the ECPR pricing rule, the MCP is 50 (*Yuan/tonne*).

According to ECPR allocation rule, generator 1 to 4 allocated allowances is 199680, 300160, 300160, and 0 (*tonne*) respectively. Based on (14), the new market saves 10.4% emission. So the new market indeed can effectively realize mitigating CO2 emission.

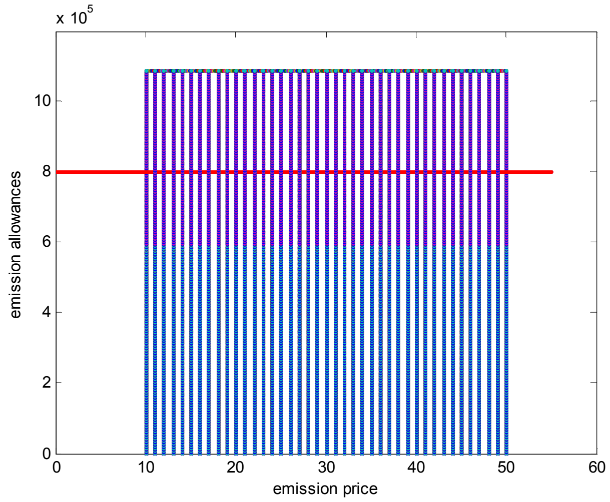

Figure 4. *Market demand curve and equilibrium.*

7. Conclusions

In order to effectively motivate generator mitigating emission on condition of electric power satisfying the national economy development, this paper develops a new emission market for allowances allocation. It refers to major features of existing emission market. And it is improved in, (i) electricity-environment coordinated regulation, (ii) adopting the first price-quantity sealed auction for allowances allocation, (iii) penalty covering generator's all emissions, and (iv) pricing emission by market bidding process and regulatory process coordinately. In lieu with supply function equilibrium model, we construct a stochastic parameter linear programming model to depict generator's decision, which provides us its bidding curve. According to market equilibrium, each generator gets its allowances at a MCP price. We found that, (i) the new market can not only effectively motivate generator to mitigate emission individually, but also can save allowances through market process; (ii) it can be a good instrument to pricing emission allowances. So it is truly an effective way to organize emission market based on electricity-environment coordinated regulation. Finally, we present a numerical simulation for testing its validity, and the results are well fitted to our theoretical conclusions.

Acknowledgements

This paper is supported by Natural Science Foundation Project of CQ CSTC (Project No. cstc2012jjA20013) and Chongqing University of Arts and Sciences Project (Project No. R2012JG04). The author is solely responsible for any errors or omissions.

References

[1] Leslie Nielson. (2008). The European emissions trading system—lessons for Australia. Research paper No.3: ISSN 1834-9854.

[2] Lene Nielsen, Tim Jeppesen. (2003). Tradable green certificates in selected European countries—overview and assessment. Energy Policy 31: pp 3-14.

[3] Sorrell, S. Sijm, J. (2003). Carbon trading in the policy mix. Oxford. Review of Economic Policy 19: pp 420-437.

[4] Tang Shongling, Ren Yulong. (2008). Coordinated regulation: electricity regulation system and theoretic innovation. Management World 7: pp 174-175.

[5] Rosendahl, K. (2004). Cost-effective environmental policy: implications of induced technological change. Journal of Environment Economy Manage 48: pp 1099-1121.

[6] Meyer NI, (2003). European schemes for promoting renewables in liberalized markets. Energy Policy 31: pp 665-676.

[7] Emilie Alerola, Julien Chevallier, and Benoit Cheze. (2009). Emissions compliances and carbon prices under the EU ETS: a specific analysis of industrial sectors. J. Policy Modeling 31: pp 446-462.

[8] Klepper, G. and Peterson, S. (2006). Emissions trading, CDM, JI, and more: the climate strategy of the EU. Energy Journal 27: pp1-26.

[9] Sijm, J. Neuhoff, K. and Y. Chen. (2006). CO2 cost pass-through and windfall profits in the power. Climate Policy 6: pp 49-72.

[10] Montgomery, W. (1972). Markets in licenses and efficient pollution control programs. Journal of Economic Theory 5: pp

395-418.

[11] Mandell, S. (2008). Optimal mix of emissions taxes and cap-and-trade. Journal of Environment Economy Manage 56: pp131-140.

[12] Fredrik Pettersson. (2007). Carbon pricing and the diffusion of renewable power generation in Eastern Europe: a linear programming approach. Energy Policy 35:pp2412-2425.

[13] Michael Gillenwater and Clare Breidennich. (2009). Internalizing carbon costs in electricity markets: using certificates in a load-based emissions trading scheme. Energy Policy 37: pp 290-299.

[14] Ivana Kockar, Conejo, AJ and McDonald, JR. (2009). Influence of the emissions trading scheme on generation scheduling. Electrical Power and Energy Systems 31: pp 465-473.

[15] Sijm, J. Bakker, S. Chen, Y. and Harmsen, H. (2005). CO2 price dynamics: the implications of EU emissions trading for the price of electricity. ECN Report. ECN-C-05-081.

[16] Klemperer, D. and Meyer, M. (1989). Supply function equilibria in oligopoly under uncertainty. Econometrica 57: pp 1243-1277.