Research Journal of Applied Sciences, Engineering and Technology 6(21): 3993-4002, 2013
ISSN: 2040-7459; e-ISSN: 2040-7467

Submitted: January 25, 2013 Accepted: March 02, 2013 Published: November 20, 2013

The Power Generation Capacity Investment Model Basing on the Newton KKT Interior-point Method under the Market Environment of Low Carbon

Zeng Ming, Ma Shaoyin, Ma Mingjuan, Xue Song and Shi Hui
School of Economics and Management, North China Electric
Power University, Beijing 102206, China

Abstract: Under the market environment of low carbon, whether renewable energy can obtain the power for sustainable development, promote the goal of the whole society and make money for investors depends on the rational optimization of power investment capacity and achieving power generation resources coordinated scheduling. This study constructs an expansion model of the generation capacity investment taking oligopoly, policy tools, carbon emissions trading right and green certificate system into account and uses the case analysis of the impact of ETS mechanism and the Tradable Green Certificate mechanism on power generation enterprises investment capacity with Newton KKT interior-point method. This study can also provide a strong decision basis for policy making.

Keywords: Carbon emissions trading, generation capacity investment model, green certificate, Newton KKT interior-point method, oligopoly

INTRODUCTION

Florentin (1996) have pointed that under the double pressure of the improving of international carbon reduction and domestic economic growth, China develop low-carbon economic development ideas and goals, clean energy and achieve the green growth, into the "Twelfth Five-Year Plan" plan which requires that the new energy industry should focus on developing renewable energy, such as wind power. Ming *et al*. (2011) and You-Hua *et al*. (2010) have discussed the rapid growth of power demand and the coal-dominated energy structure which are the two basic characteristics of China's power industry. Stéphanie and Philippe (2010) and Jing *et al*. (2011) have put forward China's scientific, green, low carbon energy deployment in the period of the “Twelfth Five-Year”, to speed up the adjustment of energy structure and develop new energy industry vigorously, in order to implement the proportion of non fossil energy consumption to increase to 15% target before 2020. Therefore, adjusting China's current power structure, reducing the proportion of coal and vigorously developing clean energy, can not only meet the energy strategy of our country, but also meet the requirements of building a modern energy industry system.

With the development of renewable energy power generation technology and external requirements of developing low carbon power, connecting renewable energy to the grid has been the main focus of multi-stakeholder participation bodies. Chunbo and David (2008) and Xiong and Qi (2011) have investigated the increasing of the capacity of renewable energy grid-connected under the support of new technology and policy. Djamel and Ibrahim (2009) have pointed that the operation of power system needs to strictly maintain the real-time balance between total supply and total demand of electricity. However, because of the characteristic of renewable energy power generation, for example intermittent, random and low mass access scheduling, there will be a great impact on the power grid operation after large-scale accessed. Therefore, whether renewable energy can obtain the power for sustainable development, promote the goal of the whole society and make money for investors depends on the rational optimization of power investment capacity and achieving power generation resources coordinated scheduling. Valle *et al*. (2009) and Wang *et al*. (2012) have discussed that influence of wind power and solar and other renewable energy power generation on power system not only depends on the scale grid-connected renewable energy, but also depends on the investment plan and operation (scheduling) of the capacity of the power system. Zeng *et al*. (2011) set up a new portfolio optimization model of power capacity in conditions of considering grid-connected wind and carries out China's best wind power installed capacity and the scale of investment for the present stage combining with examples. Onno and Marjan (2010) set up a dynamic investment model of power capacity and solve the model with dynamic programming. Zhang *et al*. (2012) set up an optimal portfolio investment model of generation capacity with the consideration of environmental cost, at the same time does the corresponding numerical example analysis with the immune particle swarm algorithm. Feng-Ting and Qin

Corresponding Author: Zeng Ming, School of Economics and Management, North China Electric Power University, Beijing 102206, China

(2007) present hydro and wind power system day joint peaking operation strategy in the winter dry season. The existing literature has conducted the research to the influence of grid-connected renewable energy on the stability and security of power system. One of the key problems to be solved in power system is to integrate a plurality of electricity load and power resources in order to improve the reliability of power supply system and reduce the cost of power system operation. The optimization of generation capacity investment requirements ensures that both meet the load and operation requirements and not excessive investment waste. Therefore, this study constructs an expansion model of the generation capacity investment account of oligopoly, policy tools, carbon emissions trading right and green certificate system and uses the case analysis of the impact of ETS mechanism and the Tradable Green Certificate mechanism on power generation enterprises investment capacity with Newton KKT interior-point method.

MATERIALS AND METHODS

Introduction: The electricity market in this study is established as follows: In the short-term electricity market, power generation enterprises compete with each other basing on the generating capacity. While in the long-term, as assumed in the Cournot model, power generation enterprises compete on the basis of power generation capacity. For each generation enterprise, maximize profits is subject to specific technical constraints and the structure of the problem corresponds to a variety of simultaneous optimization problems. In the electricity market, carbon emissions permits market and green certificate market, the optimization problems can be combined together through the tariff and carbon emissions permission price which is generated by the interaction.

The business goal of each generation enterprise is to maximize profit which equals to market income minus operating costs, investment costs and the cost of buying carbon emissions permission. The set of constraints *m* and *g* are set to ensure that the decision variable in each generation enterprise optimization program is technically feasible. What's more, *g* considers the requirements that the decision variables are rounded to the nearest whole set of constraints. From the view of form, the model constructed in this study is a Nash strategy (X, P), where *x* stands for strategic decision set, $x = (x_1, ..., x_E)$; *P* stands for profit set, $P = (P_1, ..., P_E)$, *e* stands for a power generation enterprise, e = (1, ..., E,). Therefore, the Nash equilibrium is a set of strategic decisions x^*_e.

The assumptions of power generation expansion model are as follows:

- In order to ensure the reasonableness of the solution, it is assumed that *m* and *g* are linear.
- The carbon emissions trading market is assumed as a perfectly competitive market. So for power generation enterprises, the market-clearing price is the intersection of the demand curve and the supply curve of total carbon emissions. The supply curve stands for carbon emissions permissions constant set by the government, while the demand curve is the sum of the carbon emission demand in all sectors.
- It is assumed that the green certificates market is a perfectly competitive market. And renewable energy generation capacity of all power generation enterprises must be greater than the quota set by the government.
- It is assumed that the power generation enterprises develop its power generation capacity expansion strategy in the form of Cournot competition whose assumption means that when it is simulated, the investment strategy will be formed. That is to say each generation enterprise will choose the new maximum productivity in order to maximize the profit.

Objective function: The goal of the power generation enterprises is to maximize the profits. The objective function refers to Eq. (1):

$$\sum_t \sum_n T_{tn} \cdot (i_t \cdot P_E \cdot Q_E) + \sum_t \sum_n D_{t,n} \cdot [\sum_{ce \in e} i_t \cdot C_{ce} \cdot (R_{ce} \cdot Q_{ce,t,n} + R_{ce,t,n} \cdot t^2_{ce,t,n}) + \sum_{cn \in e} i_t \cdot v_{cn} \cdot (R_{cn} \cdot Q_{cn,t,n} + R_{cn} \cdot t_{cn,t,n} + R_{cn} \cdot t^2_{cn,t,n})] - \sum_{cn \in e} \sum_{t>1} i_t \cdot CI_{cn} \cdot (I_{cn,t} - I_{cn,t-1}) - \sum_{st} i_{st} \cdot P_X \cdot (Q_X - r_X) \tag{1}$$

where,

- i_t : The discount rate in the period *t*
- P_E : The tariff on the load level *n* in the period *t* (Yuan/kWh)
- Q_E : Electricity sales of power generation enterprise *e* on the load level *n* in the period *t* (kWh)
- $T_{t,n}$: The duration on the load level *n* in the period *t* (kh)
- C_{ce} : The fuel cost of thermal power technology *ce* (Yuan/Mcal)
- R_{ce} : The heat consumption rate of current thermal power technology *ce*
- $Q_{ce,t,n}$: The generating capacity of current thermal power technology *ce* on the load level *n* in the period *t* (GW)
- R_{cn} : The heat consumption rate of emerging thermal power technology *cn*
- $Q_{cn,t,n}$: The generating capacity of emerging thermal power technology *cn* on the load level *n* in the period *t* (GW)
- CI_{cn} : Capacity investment cost (million Yuan/GW)
- $I_{cn,t}$: Newly installed capacity of emerging thermal power technology *cn* in the period *t* (GW)
- $I_{cn,t-1}$: Newly installed capacity of emerging thermal power technology *cn* in the period *t-1* (GW)
- i_{st} : The discount rate in the sub-period st
- P_X : Carbon emission permission price in the period *t* (Yuan/tCO_2)
- Q_X : Electricity sales of power generation enterprise *e* on the load level *n* in the period *t* (kWh)

r_X : The initial allocation of carbon emissions permission of power generation enterprise *e* in the period *t* (million tons CO_2)

Auxiliary equation: As is shown in Eq. (2) below, total generating capacity of the power generation enterprises is the generating capacity of all generation units, including thermal power units, hydroelectric units, pumped storage units and small hydropower units:

$$Q_T = \sum_{ce \in e} Q_{ce} + \sum_{cn \in e} Q_{cn} + \sum_{h \in e} Q_h - \sum_{b \in e} Q_b + \sum_{f \in e} Q_f \quad \forall e, n \qquad (2)$$

where,

Q_T : The total generating capacity of power generation enterprises (GWh)

Q_{ce} : The generating capacity of current thermal power technology *ce* in the period *t* (GWh)

Q_{cn} : The generating capacity of emerging thermal power technology *ce* in the period *t* (GWh)

Q_h : The generating capacity of pumped storage units *h* in the period *t* (GWh)

Q_b : The electricity consumption for power generation of pumped storage units *h* in the period *t* (GWh)

Q_f : The generating capacity of small hydropower units *f* in the period *t* (GWh)

Equation 3 illustrates that the carbon emissions permission provided by the government is the sum of that purchased by the non-power generation enterprises and all power generation enterprises:

$$q_{st}^n = Q_{st} - \sum_e q_{e,st}^M \qquad \forall st \qquad (3)$$

where,

$q_{s,t}^n$: The carbon emissions permission owned by the non-power generation enterprises in the period *t* (million tons CO_2)

Q_{st} : The carbon emissions permission provided by the government in the period *t* (million tons CO_2)

$q_{e,st}^M$: The carbon emissions permission owned by power generation enterprise *e* in the period *t* (million tons CO_2)

As is shown in Eq. (4), tariff is a linear function of electricity sales of the power generation enterprises:

$$P_E = Q_N - l_t \cdot (\sum (Q_E - Q_N) \qquad \forall t \qquad (4)$$

where,

Q_N : Electricity demand in the current tariff case in the period *t* (GWh)

l_t : The slope of the electricity demand curve in the period *t* (Yuan/kWh) /GW)

As is shown in Eq. (5), the carbon emissions permission price is a linear function of the total purchased electricity of power enterprises:

$$P_M = l_{st}^M \cdot (\sum_e q_{e,s}^M + q_{st} - Q_{st}) \qquad \forall st \qquad (5)$$

where,

P_M : The carbon emissions permission price in the sub-period *st* (Yuan/tCO_2)

l_{sp}^M : The carbon emissions permission price of the non-power generation enterprises in the *st* sub-period (yuan/tCO_2)

Constraints:

Hydropower units scheduling constraints: As is shown in Eq. (6), the generating capacity in each period is a function of that of hydropower units and pumped storage units on each load level, subject to water flow, initial storage capacity and the ultimate capacity in this period:

$$\sum_n D_{t,s,n} \cdot h_{h,t,s,n} - R_{h,t,s} + R_{h,t,s+1} - A_{h,t,s} \leq 0 \perp \mu_{h,t,s}^R \;\; \forall st \qquad (6)$$

where,

$R_{h,t,s}$: The initial water storage of hydropower units *h* at the moment *s* in the period *t* (TWh)

$R_{h,t,s+1}$: The initial water storage of hydropower units *h* at the moment *s+1* in the period *t* (TWh)

$A_{h,t,s}$: The water injection of hydropower units *h* in the period *t* (TWh)

$\mu_{h,t,s}^R$: The scheduling constraints of hydropower units *h* in the period *t* (million Yuan/MW)

Pumped storage units scheduling constraints:

$$\sum_n D_{t,s,n} \cdot (h_{b,t,s,n} - \rho_b \cdot b_{b,t,s,n}) \leq 0 \;\; \perp \mu_{b,t,s}^R \;\; \forall t, s, b \qquad (7)$$

$$\sum_n D_{t,s,n} \cdot h_{b,t,s,n} \leq \bar{R}_b \;\; \perp \mu_{b,t,s}^{\bar{R}} \quad \forall t, s, b \qquad (8)$$

where.

ρ_b : The performance of the pumped storage units (p.u.)

$b_{b,t,n}$: The power consumption of pumped storage units *b* in the period *t* (GW)

$\bar{R}_b$: The maximum water storage of pumped storage units *b* (TWh)

$\mu_{b,p,s}^{\bar{R}}$: The largest hydropower capacity reserve boundaries of pumped storage units *b* in the period *t* (million Yuan/MW)

Investment constraints: The total installed capacity in any period is greater than or equal to that in the previous period:

$$I_{cn,t-1} - I_{cn,t} \leq 0 \;\; \perp \mu_{cn,T}^{TA} \quad \forall t > 1, cn \qquad (9)$$

$$t_{cn,t,s,n} \le \phi_{cn} \cdot I_{cn,t} \quad \perp \mu^{I}_{cn,t,s,n} \quad \forall t,s,n,cn \tag{10}$$

$$\sum_{cn\in e} ci_{cn} \cdot (I_{cn,t} - I_{cn,t-1}) \le FI_{e,t} \quad \perp \mu^{FI}_{e,t} \quad \forall t>1,e \tag{11}$$

Equation 9 illustrates that the total installed capacity in any period is greater than or equal to that in the previous period. Equation 10 illustrates that new power plant's generating capacity in each period is less than or equal to its installed capacity.

where,

- $I_{cn,t-1}$ & $I_{cn,t}$: New installed capacity of thermal power technology *cn* in the period *t* and *t-1* respectively (GW)
- $\mu^{TA}_{cn,t}$: The increasing maximum installed capacity constraints (million Yuan/MW)
- φ_{cn} : Unit utilization coefficient of emerging thermal power technology *cn* (p.u.)
- $I_{cn,t}$: New installed capacity of thermal power technology *cn* in the period *t* (GW)
- $\mu^{I}_{cn,t,s,n}$: The generating capacity constraints of emerging thermal power technology *cn* in the period *t* (million Yuan/MW)
- $\bar{F}I_{e,t}$: The investment of power generation enterprise *e* in the period *t* (million Yuan)
- $\mu^{FI}_{e,t}$: The investment constraints of power generation enterprise *e* in the period *t* (p.u.)

Carbon emissions permission constraints: As is shown in Eq. (12), the amount of carbon dioxide emitted into the atmosphere is subject to the carbon emissions permission of each enterprise:

$$\sum_{t\in st}\Big(\sum_{ce\in e,s} D_{t,s}\cdot(\tau_{ce}\cdot p_{ce,t,s}) + \sum_{cn\in e,s} D_{t,s}\cdot(\tau_{cn}\cdot p_{cn,t,s})\Big) \le q^{排}_{e,st} \quad \perp \mu^{q}_{e,st} \quad \forall e,st \tag{12}$$

where,

- τ_{cn} & τ_{ce} : The carbon emissions rate of thermal power technology *cn* and *ce*, respectively (ten thousand tons CO_2/MW)
- $P_{ce,t}$ & $P_{cn,t}$: The tariff of thermal power technology *cn* and *ce* in the period *t* respectively
- $\mu^{q}_{e,st}$: The carbon emission constraints of power generation enterprise *e* in the sub-period s*t* (million Yuan/million tons CO_2)

Tradable green certificate constraints: As is shown in Eq. (13), the unit generating capacity of each load level is less than or equal to the installed capacity multiplied by its utilization coefficient:

$$tr_{cn,t,s} \le \phi_{cn} \cdot Ir_{cn,t} \quad \forall t,s,cn\in cr \tag{13}$$

where,

- $tr_{cn,t,s}$: The generating capacity of renewable energy generation technology cr ∈ cn in the period *t* (GW)
- $Ir_{cn,t}$: The new installed capacity of renewable energy generation technology cr ∈ cn in the period *t* (GW)

As is shown in Eq. (14), cumulative installed capacity is a monotonically decreasing function of time:

$$Ir_{cn,t-1} - Ir_{cn,t} \le 0 \quad \forall t, cn\in cr \tag{14}$$

where,

- $Ir_{cn,\,t-1}$: The new installed capacity of renewable energy generation technology cr ∈ cn in the *t-1* period (GW)

The total generating capacity of the current and new renewable energy generation technologies involved in the tradable green certificate market is greater than or equal to the regulators' minimum amount:

$$\sum_{ce}\sum_{s,n} D_n \cdot tr_{ce,t,s,n} + \sum_{cn}\sum_{s,n} D_n \cdot tr_{cn,t,s,n} \ge E_{t,cr} \quad \forall ce\_cn\in cr,t,s,n \tag{15}$$

where,

- D_n : The duration on the load level *n* (h)
- $tr_{ce,\,t,\,s,n}$: The generating capacity of renewable energy generation technology cr ∈ cn in the period *t* (GW)
- $E_{t,cr}$: The generating capacity of renewable energy generation technology owned Green certificates *cr* in the period *t* (kWh)

Linear complementarity problem: The generation capacity Investment model constructed in this study is a Linear Complementarity Problem (LCP), which is a cross field between Operations Research and Computational Mathematics and has a wide range of applications in the economics and engineering. Containing complementarity condition is the most significant feature of the linear complementarity problems, which requires the component corresponding to the two set of non-negative variables are multiplied by zero.

Assuming that $M \in R^{n\times n}$ and $q \in R^n$, if we can find $w = (w_j) \in R^n$ and $z = (z_j) \in R^n$ meeting w-Mz = q, w, z≥0 and $wz^T = 0$, the problem will be a linear complementarity problem denoted by LCP (q, M). If $z \in R^n$, we define $h_i(z) = \min\{z_j, (q + Mz)_i\}$ and $h_i(z) = \min\{h_i, (z)\}$, then $h(z): R^n \rightarrow R^n$ is a piecewise linear concave function. Solving the LCP (q, M) problem is equivalent to solving piecewise linear equation. On the contrary, under the nonsingular hypothesis conditions, any piecewise linear equations can be used as linear complementarity problems.

Newton KKT interior-point method: At present, there are many algorithms to solve linear complementarity problem, but these algorithms typically have its own limited conditions. Through the development in recent decades, people not only have improved and enriched the theoretical research of linear complementarity problems, but also have put forward a lot of efficient algorithms, for example, the smooth and non-smooth equations method, minimization method, GLP projection method, interior-point method, smooth Newton method and so on. French scholar P.-A. Absil has proposed Newton KKT interior-point method to solve quadratic programming problems. The method is the combination of Newton method and KKT conditions, weakening the constraints of quadratic programming problems, but it requires that the matrixes of quadratic programming problems are symmetric.

Consider the following quadratic programming problem:

$$\min f(x) = \frac{1}{2}\langle x, Hx\rangle + \langle c, x\rangle \text{ s.t. } A(x) \le b,\ x \in R^n$$

where, $A \in R^{m\times n}$, $b \in R^m$, $c \in R^n$ and $H \in R^{n\times n}$ are symmetric matrixes. Assuming $I = \{1, \ldots, m\}$, where *m* is the row number of matrix *A*; if $i \in I$, let a_i to be the transpose of the *i-th* row of *A*, b_i is the element of the *i-th* row of *A* and $g_i(x) = <\alpha_i, x> - b_i$, then feasible region is denoted by $F: = \{x \in R^n: g_i(x) \le 0, \forall i \in I\}$.

The parameters and calculation steps of Newton KKT interior-point algorithm are as follows:

Parameters: $\beta \in (0,1),\ \underline{z} \succ 0, z_u \succ 0, \sigma \succ 0, \gamma \succ 0.$

Data: $x^0 \in F^0, z_i^0 \succ 0, \forall i \in I.$

Initial step: Let k = 0, $\bar{I}:= \emptyset, \bar{a}_i := 0, \forall i \in I, \bar{E} := I.$

Step 1: $W^k: = H + E^k$ where, $E^k \ge 0$; E^k are obtained by the following method:
If $H \ge \sigma I$, let $E^k: = 0$; otherwise $\bar{E} \neq 0$
If $\exists i \in \bar{I}$, meeting $\frac{z_i^k}{|g_i(x^k)|} \le \bar{a}_i$ or ($\bar{E} \neq 0$ and $\bar{I} = \emptyset$) and $\frac{z_i^k}{|g_i(x^k)|} \ge \gamma^2 \bar{a}_i$, then:

- Let $\bar{I} = \left\{i: \frac{z_i^k}{|g_i(x^k)|} \ge 1\right\}, \bar{a}_i := \frac{1}{\gamma}\frac{z_i^k}{|g_i(x^k)|}, i \in \bar{I}$
- If $H + \sum_{\bar{I}_i} \bar{a}_i a_i a_i^T \ge \sigma I$, let $\bar{E}: = 0$; otherwise let $\bar{E} \ge 0$ and $\bar{E} \le (\|H\|_F + \sigma)I$, meeting $H + \sum_{\bar{I}_i} \bar{a}_i a_i a_i^T \ge \sigma I$

Let $E^k := \bar{E}$.

Step 2: Calculate the search direction. Suppose (Δx^k, ζ^k) is the solution of the following linear system in the (Δx, ζ) situation:

$$W^k \Delta x - A^T \varsigma = -\nabla f(x^k),\quad z_i^k \langle a_i, \Delta x\rangle + g_i(x^k)\varsigma_i = 0,\ \forall i \in I$$

If $\Delta x^k = 0$, end.

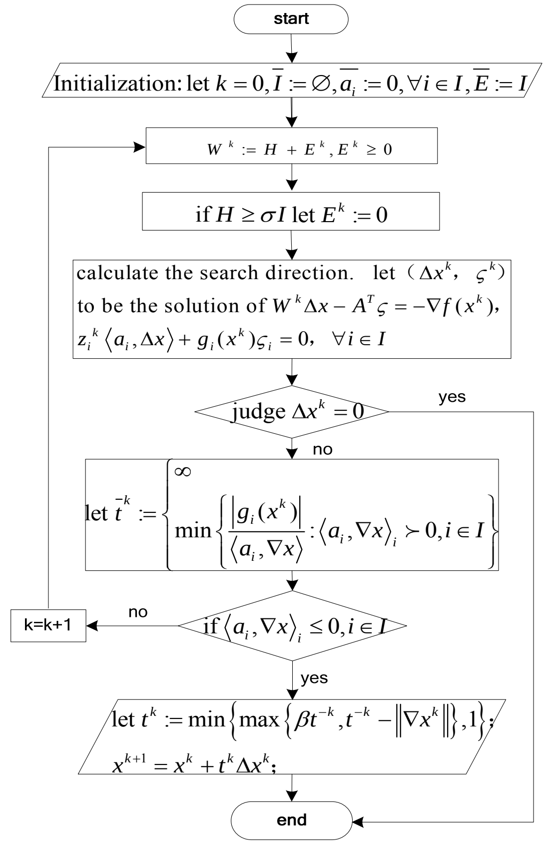

Fig. 1: The flowchart of Newton KKT interior-point method

Step 3:

- Let $t^{-k}: = \begin{cases}\infty \\ min\left\{\frac{|g_i(x^k)|}{\langle a_i, \nabla x\rangle} : \langle a_i, \nabla x\rangle_i \succ 0, i \in I\right.\end{cases}$
  If $\langle a_i, \nabla x\rangle_i \le 0, i \in I$, let $t^k: = \min\{\max\{\beta t^{-k}, t^{-k} - \|\nabla x^k\|\}, 1\}$ and $x^{k+1} = x^k + t^k \Delta x^k$.
- Let $(\varsigma^k)_i := \min\{\varsigma_i^k, 0\}, \forall i \in I$ and $z_i^{k+1} := \min\{\max\{\min\{\|\Delta x^k\|^2 + \|\varsigma^k\|^2, \underline{z}\}, \varsigma_i^k\}, z_u\}, \forall i \in I$.
- Let k = k+1, turn to step one.

Figure 1 is a flow chart of the Newton-KKT interior-point algorithm.

RESULTS AND DISCUSSION

Introduction: Basing on Newton KKT interior-point method, this study combines with the above model to simulate the impact of ETS and tradable green certificate market on the capacity investment of a regional power generation enterprise. The numerical example analyses the generation capacity investment trend of the regional electricity system over the next 16 years (2005-2020). And the system includes a total of six power generation enterprises. Consider the main power generation technologies, including Nuclear (NCL), Fuel Oil (FO), Natural Gas (GN), Combined

Table 1: Parameters for current thermal power plants (CSEN, 1997)

Power generation enterprises	Power generation technology	Linear variable costs (Yuan/MWH)	Secondary variable costs (Yuan/MW^2H)	Installed capacity (MW)	CO_2 emission rate (T/MWH)
1	HLL-4	15635	0.50	544	0.90
	LGN-2	14862	4.32	400	0.94
	FO-4	30673	2.91	682	0.76
2	CCGT-4	16442	1.66	800	0.40
3	CCGT-1	18063	1.33	1500	0.40
	NCL-2	2743	0.17	3641	0.00
	HLL-2	14837	0.50	1462	0.96
	LGP-1	15336	0.58	1469	0.99
	LGN-1	16508	0.00	1100	0.93
	CI-2	11471	0.17	1712	0.92
	FO-2	36708	2.12	400	0.77
	GN-2	33790	17.62	1543	0.72
4	CCGT-2	16442	1.16	1200	0.40
	NCL-3	22801	0.03	739	0.00
	HLL-3	12718	0.24	1498	0.90
	LGP-2	14339	0.00	583	1.27
	FO-3	34413	6.15	447	0.76
	GN-3	35062	0.00	155	0.99
5	NEL-1	2743	0.17	3358	0.00
	HLL-1	12468	3.41	1021	0.95
	CI-1	12968	0.00	220	0.90
	FO-1	34414	1.08	2337	0.78
	GN-1	32668	2.91	830	0.79
6	NCL-4	2893	0.00	165	0.00
	HLL-5	12219	3.41	1588	0.92
	CCGT-3	21230	0.00	450	0.40
Others	CCGT-5	19152	0.00	400	0.40

Table 2: Parameters for renewable and cogeneration power plants (CSEN, 1997)

Power generation enterprises	Power generation technology	Linear variable costs (Yuan/MWH)	Installed capacity (MW)	Unit utilization (%)	CO_2 emission rate (T/MWH)
Specification	EBIO	6487	436	0.413	0.00
	ECOG	23978	5785	0.319	0.55
	EMINH	0	1637	0.305	0.00
	EEOL	0	7782	0.211	0.00
	ESOL	0	16	0.107	0.00

Table 3: Parameters for current hydro power plants (CSEN, 1997)

	REG		FLU	BOMB		
Power generation enterprises	Max. power (MW)	Avg. annual water injection (GWH)	Max. power (MW)	Max. power (MW)	Pumping yield (%)	Max. capacity (GWH)
1	475	243	41	340	70	50
2	0	0	0	0	70	0
3	2100	2839	390	1409	70	515
4	850	1538	188	208	70	90
5	3150	8930	360	628	70	300
6	270	264	38	0	70	0
Others	0	0	0	0	70	0

Max.: Maximum; Avg.: Average

Table 4: Parameters for new technologies

Power generation technology	Linear variable costs (Yuan/MWH)	Investment cost (Yuan/KW)	Max. power (MW)	Unit utilization (%)	CO_2 emission rate (T/MWH)
CCGT	17442	3871		1.000	0.40
NCLAV	6561	16611		1.000	0.00
CSC	12467	8239		1.000	0.80
BIO1	41669	10654	1131	0.799	0.00
BIO2	8331	11678	1212	0.799	0.00
BIO3	55548	9485	687	0.799	0.00
MINH	0	22425	743	0.267	0.00
COG	39037	4983	1315	0.426	0.63
EOL1	0	7475	2444	0.247	0.00
EOL2	0	7475	3665	0.212	0.00
EOL3	0	7475	6109	0.159	0.00
SOLT	0	49833	200	0.109	0.00

Max.: Maximum

Cycle Gas Turbine (ECCGT), civil coal (HLL), Coal Imported (CI), gray Lignite (LGP), black Lignite (LGN), Adjustable hydropower station (REG) riverbed-hydroelectric station (FLU), pumping unit (BOMB), Biomass (EBIO) Cogeneration (ECOG) small Hydropower (EMINH) wind Energy (EEOL) and Solar Energy (ESOL). In addition, due to the new direction of investment, we also consider the newly generation technologies which will possibly large-scale develop in the future: Supercritical Coal-fired (CSC), Nuclear Advanced (NCLAV), Combined Cycle Gas Turbine (CCGT), three types of raw substances (BIO1: crops energy BIO2: agricultural waste, BIO3: forest waste), divided according to the size of the wind speed, the three types of wind energy (EOL1, EOL2, EOL3), small Hydro (MINH) Cogeneration (COG) and Solar Thermal (SOLT).

The related parameters of the example can refer to Table 1 to 4.

Other parameter assumptions and data of the example are described as follows:

- In carbon emission rights market, the emissions permission is determined by a regional National Allocation Plan (RD 60/2005), i.e., 1.6 million tons. However, according to statistics, the plan has only been implemented in the period 2005-2007. Since 2008, the government has regulated that the emissions should not be higher than 24% of the 1990 emissions. That is to say the number of emissions from 2008 to 2014 should be 1.478 million tons. However, this is all emissions permissions of all sectors covered by the ETS system can be assigned. Because of the dispersion of other industries and the availability of data, this study only models the power industry and analyses the example.
- With regard to the tradable green certificate system, according to the EU Renewable Energy Directive 2001/77, the renewable energy quota is expected to reach 17.5% in 2010.
- According to the estimation of a regional government, it is assumed that average annual growth rate of the electricity demand is 2.5% and investment discount rate is 9%.
- According to the average annual growth rate of electricity demand, the electricity demand curve slope is 600 Yuan/MWh. MW and the two largest current enterprises' surplus demand curve slope is 1.3 Yuan/MWh.MW.

Results analysis: The fusion complementary problem and cost minimization problem modeled in this study are solved by the PATH solver and CPLEX solver respectively. With regard to the new investment aspect, the main indicators of the example include electricity tariff, installed capacity, costs and profits. In order to simplify the calculation, only simulation results in the next few years have been analyzed. To verify the simulation results and determine the effectiveness of the oligopoly model, we run the model in a perfectly competitive market situation. The simulation results of the example are shown in Table 5 to 8:

As we can see from the simulation results, in line with the expectations, if there is no emission trading scheme, the level of the tariff in the electricity market will be lower. In the case of oligopolistic market, there will be little change in the way that the system works, but the price will be increased. Assuming that elasticity of demand is nonzero, we can see from the

Table 5: Prices and emissions

		2005	2012	2020
Basic example	Tariff (Yuan/MWh)	215.00	225.00	227.000
	CO_2 emissions (million tons)	90.61	114.68	138.900
Consider the ETS	Tariff (Yuan/MWh)	222.00	250.00	300.000
	CO_2 emissions (million tons)	89.70	82.24	81.090
	CO_2 emissions permission price (Yuan/ton)	0.00	6.01	22.050
Consider the TGC	Tariff (Yuan/MWh)	208.00	225.00	227.000
	CO_2 emissions (million tons)	80.17	97.15	116.710
	Green certificate price (Yuan/MWh)	14.98	26.27	56.590
Consider the ETS and TGC	Tariff (Yuan/MWh)	208.00	244.00	275.000
	CO_2 emissions (million tons)	80.17	81.54	81.720
	Green certificate price (Yuan/MWh)	0.00	39.87	122.180
	Green certificate price (Yuan/MWh)	124.41	198.84	422.030

Table 6: Installed power in 2020 per technology (MW)

Power generation technology	Basic example	Consider the ETS	Consider the TGC	Consider the ETS and TGC
CCGT	9988	18967	7310	12723
CSC	2333			
BIO1			1021	1021
BIO2		1094	1094	1094
BIO3			225	225
EOL1		2206	2206	2206
EOL2			3308	3308
EOL3			5513	5513
合计	12321	22267	20676	26089

Table 7: Electricity produced in 2020 per technology

	Basic example (%)	Consider the ETS	Consider the TGC	Consider the ETS and TGC (%)
NCL	24.48			24.48
HLL	16.27			11.15
LGP	5.99			2.41
LGN	4.01			1.21
CI	5.98			5.88
ECCGT	4.80			6.28
EBIO	0.56			0.56
ECOG	5.72			5.72
EMINH	1.55			1.55
EEOL	5.09			5.09
ESOL	0.01			0.01
REG	5.41			5.41
FLU	3.49			3.49
CCGT	9.32			16.89
CSC	7.34			
BIO1				0.81
BIO2				3.00
BIO3				0.05
EOL1				1.87
EOL2				2.15
EOL3				2.00
Total	100			100

Table 8: Costs and profits (million Yuan)

	Basic example	Consider the ETS	Consider the TGC	Consider the ETS and TGC
Generation cost	32661	36840	37578	39731
Consumption cost	66462	74258	72783	76838
Profit	33800	37418	35205	37107
Enterprise 1	100			340
Enterprise 2	-153			234
Enterprise 3	10394			10501
Enterprise 4	2690			3019
Enterprise 5	9205			9736
Enterprise 6	715			826
Other enterprises	-135			77
REGESP*	10984			12373

simulation results, that the generating capacity of power generation enterprises is low and emission permission is less, too. Those lead to reduce the carbon emissions permission price, thus decreasing the tariff. What's more, by comparing the two market hypothesis, we can find that there are greater differences between them. And it is reasonable to use the oligopoly method in the example.

As can be seen from Table 5, with the implementation of ETS mechanism, the tariff level rises and carbon emissions reduce. In 2008, the region appeared carbon emissions permission price, which is because there appears carbon emissions permission surplus in the first stage. Through tradable green certificate mechanism, renewable energy generation technology was introduced in the power system, thus there has also been a green certificate price.

Through comprehensive analysis, we find the green certificate market; the carbon emissions market and the electricity market are interaction and mutual influence mainly in the following two aspects.

On the one hand, we introduce of the TGC quota mechanism in the electricity market to reduce the system demand for traditional energy supply, so that the tariff reduces, i.e., TGC quota mechanism is an indirect way to reduce the tariff. By the way of increasing the share of renewable energy generation, the carbon emissions permission price decreases, thereby reducing the tariff which reflects the marginal cost of abatement. Therefore, even in the case of the carbon emissions permission price in 2012 or 2020, electricity tariff is still lower than that under TGC mechanism.

On the other hand, the introduction of green certificates mechanism makes other effects on the electricity market. By cutting down the non-renewable energy needs, demand will become inflexible (the slope of the curve is unchanged, but the intercept is changed). Compared with the perfectly competitive market, this increases the market forces of the non-renewable energy electricity market and the oligopolistic price. However, as previously mentioned, we will get compensation from the reduced emissions permission price and the smaller non-renewable energy market.

Table 6 illustrates that considering the case of ETS and TGC, investment in thermal power will be replaced by gas-fired generation investment and the combined role between ETS mechanism and tradable green certificate system will further stimulate the development of renewable energy generation technologies. The load factors of renewable energy generation technologies are lower, so installed capacity is greater in the second case.

Table 7 depicts that as expected, ETS and TGC system have replaced the civilian coal and supercritical coal-fired power generation technology, implementing combined cycle gas turbine and renewable energy generation technologies in more large-scales.

Finally, we achieve the system's costs and profits, explained in Table 8. Table 8 also shows that the introduced ETS and TGC mechanism improve generation cost and consumption cost of the system. And there is a relatively larger increase in consumption cost.

As is shown above, despite TGC mechanism cuts down the marginal price, the total cost of the system is increased. This is because that we need to pay for the green certificate which increases the consumption cost and affects carbon emissions permission price. Therefore, the simulation results have shown that, with the introduction of the regulation in the electricity market, the profits of power generation enterprises have been improved largely. But the increase of the share is not uniform, i.e., some power generation enterprises are basically remain the same, while other power generation enterprises, usually are some small enterprises, have achieved a substantial increase in profits.

CONCLUSION

This study constructs an expansion model of the generation capacity investment accounting of oligopoly, policy tools, carbon emissions trading right and green certificate system and uses the case analysis of the impact of ETS mechanism and the Tradable Green Certificate mechanism on power generation enterprises investment capacity with Newton KKT interior-point method. The results have showed that:

- The constructed generation capacity investment model has great applicability for capacity expansion of power generation enterprises. Power generation enterprises are not major carbon emissions, which accounts for 20% of total carbon emissions, but in the carbon emissions trading mechanism, power generation enterprises are the main participants, representing as much as 50% of the emissions included in the carbon emissions trading mechanism. The model that constructed in this study is able to adequately simulate the carbon emissions of power generation enterprises.
- In regard to the power generation enterprises, although most power generation capacity investment models rely on the exogenous carbon emissions permission price, the model that constructed in this study produces endogenous carbon emissions permission prices, which provides great flexibility for the numerical example.
- Although the power generation capacity investment model presented here is not static, the simulation power generation capacity expansion mode provides a way to study the impact of electricity tariff and power generation technology on the power generation enterprises investment decisions. At the same time it has analyzed the interaction and mutual influence between tradable green certificate market mechanisms and carbon emissions, which will be the basis for future decisions in the power generation enterprises and provide a strong decision basis for policy making.

In order to improve the applicability and usefulness of the model, future researches are needed to continue. The model should give full consideration to the uncertainty and risk of the investment planning of power generation capacity. And other possible standards that are set for the enterprises' strategic development should also be taken into consideration.

REFERENCES

Chunbo, M. and I.S. David, 2008. Biomass and China's carbon emissions: A missing piece of carbon decomposition. Energ Policy, 36(7): 2517-2526.

CSEN (Comision del Sistema Electrico Nacional), 1997. Documentation Bill Electricity Sector. Electrical System Regulatory Commission of Spain (Spanish). CSEN, Madrid.

Djamel, K. and A. Ibrahim, 2009. The impact of the European Union emission trading scheme on the electricity-generation sector. Resour. Energ Econ., 33(5): 995-1003.

Feng-Ting, L. and C. Qin, 2007. Research on wind power penetration of wind-hydro-thermal power system. Renew Energ. Resour., 25(3): 68-71.

Florentin, K., 1996. The costs of mitigating carbon emissions: A review of methods and findings from European studie. Energ Policy, 24(10-11): 899-915.

Jing, T., Q. Lü, L. Guo *et al*., 2011. An inter-day combined operation strategy of hydro and wind power system for regulating peak load. Autom. Elec. Power Syst., 35(22): 97-104.

Ming, Z., Z. Jin-Rong, M. Xiang-Chun *et al*., 2011. Optimization model for generation capacity investment decision based on dynamic programming. East China Elec. Power, 39(3): 418-422.

Onno, K. and H. Marjan, 2010. Border adjustment for European emissions trading: Competitiveness and carbon leakage. Energ. Policy, 38(4): 1741-1748.

Stéphanie, M. and Q. Philippe, 2010. How to design a border adjustment for the European Union emissions trading system. Energ. Policy, 38(9): 5199-5207.

Valle, A.C.M., M.A.A. Aguiar and G. Cruz Jr, 2009. The impact of water quality as an environmental constraint on operation planning of a hydro-thermal power system. Renew Energ., 34(3): 655-659.

Wang, C., Y. Qiao and Z. Lu, 2012. A method for determination of spinning reserve in wind-thermal power systems considering wind power benefits. Autom. Elec. Power Syst., 36(4): 16-21.

Xiong, W. and H. Qi, 2011. A hybrid MCDM method for evaluating the performance of power grid. ICIC-ELB, 2(4): 891-898.

You-Hua, H., F. Da-Zhong, Q. Jun, L. Hong-Bo, N. Wei and Y. Tao, 2010. Analysis on active power fluctuation characteristics of large-scale grid-connected wind farm and generation scheduling simulation under different capacity power injected from wind farms into power grid. Power Syst. Technol., 34(5): 60-66.

Zeng, M., X. Zhang, K. Tian, S. Xue and M. MA, 2011. An optimal model of generation capacity investment portfolio considering grid-connected wind farm. Power Syst. Technol., 35(12): 153-158.

Zhang, Y., Z. Wang and J. Zhang, 2012. A statistical evaluation of power grid fault detection. ICIC-ELB, 3(1): 47-52.