Title	Power generation expansion planning model towards low-carbon economy and its application in china
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Citation	Ieee Transactions On Power Systems, 2010, v. 25 n. 2, p. 1117-1125
Issued Date	2010
URL	http://hdl.handle.net/10722/124697
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Power Generation Expansion Planning Model Towards Low-Carbon Economy and Its Application in China

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***Abstract*—Climate change poses a huge threat to human welfare. Hence, developing a low-carbon economy has become a prevailing and inevitable trend. Decarbonization of power generation, especially converting the current power mix into a low-carbon structure, will be a critical option for CO_2 emission mitigation. In this paper, an integrated power generation expansion (PGE) planning model towards low-carbon economy is proposed, which properly integrates and formulates the impacts of various low-carbon factors on PGE models. In order to adapt to the characteristics of PGE models based on low-carbon scenario, a compromised modeling approach is presented, which reasonably decreases complexities of the model, while properly keeping the significant elements and maintaining moderate precision degree. In order to illustrate the proposed model and approach, a numerical case is studied based on the background of China's power sector, making decisions on the optimal PGE plans and revealing the prospects and potentials for CO_2 emission reduction.**

***Index Terms*—Carbon capture and storage, CO_2 emission, global climate change, low-carbon economy, modeling approach, power generation expansion planning model.**

I. Introduction

CLIMATE change resulted from greenhouse gas (GHG) poses a huge threat to human welfare [1]–[3], and CO_2 contributes 77% of GHG effects. On this basis, since 2003 when the UK Energy White Paper [4] was published, developing a low-carbon economy has gradually become prevailing and inevitable. Being a major CO_2 emission source, decarbonisation in power sector is critical and fundamental in confronting the challenges of global warming. However, with long in-service lives as several decades, investments on conventional fired-based generators will lead to intensive "carbon lock-in" effect in the future [5]. Hence, it is critical to convert the current power mix into a low-carbon structure.

Manuscript received May 30, 2009; revised October 21, 2009. First published January 08, 2010; current version published April 21, 2010. This work was supported in part by Grant of State Key Lab of Power Systems (SKLD09M09), Scientific and Technical Project of State Grid, The Project Sponsored by Scientific Foundation for Returned Overseas Chinese Scholars, Ministry of Education ([2009]1001), and Program for New Century Excellent Talents in University (NCET-07-0484). Paper no. TPWRS-00398-2009.

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Digital Object Identifier 10.1109/TPWRS.2009.2036925

One of the elements in power generation expansion (PGE) is to determine the optimal mix of power generation. Generally, PGE is a large-scale mixed integer nonlinear programming problem [6], making decisions on which, where, and when new power plants should be built over a given time horizon [7]. However, with the emerging of more evidences on climate changing and CO_2 emission reduction, impacts on PGE planning incurred by various low-carbon factors should be properly considered. In [6], [8] and [9], emission control is regarded as an additional constraint in PGE model; the impacts of large-scale utilization of wind power on power system planning are evaluated in [10]; market penetrations of clean coal and carbon capture and storage technologies (CCS) are assessed considering various political as well as economical instruments in [11] and [12], respectively. However, these researches just focus mostly on some special kinds of low-carbon factors; it is necessary to develop a comprehensive PGE planning model, which appropriately integrates all kinds of low-carbon factors, including carbon trading mechanisms, low carbon generation technologies, reduction obligations, carbon tax, etc. For this purpose, a compromised modeling approach is proposed, which reasonably decreases complexities of the model, while properly keeping the significant elements and maintaining moderate precision degree. The model is denoted as low carbon power generation expansion (LCPGE) for short.

China is one of the major CO_2 emitting countries due to its coal-dominated (more than 75%) power mix. As estimation, the growth rate in GDP as well as power consumptions will remain at high level continuously in the near future. Therefore, it is of great significance to assess the potential of CO_2 emission reduction and reveal the optimal low carbon roadmap in China's power sector. For this purpose, a numerical case based on China's power sector is studied. The case study could provide better illuminations on the proposed LCPGE model and the modeling approach as well.

Generally, the paper is organized as below: The framework of LCPGE model is described in Section II; the modeling approach is introduced in Section III; formulations of the model are presented in Section IV; an illustrative example based on China's power sector applying LCPGE model is analyzed in Section V; and Section VI provides the conclusion.

II. Framework of LCPGE Model

Low-carbon factors would impose great impacts on PGE models. Firstly, carbon prices or taxes would be imposed

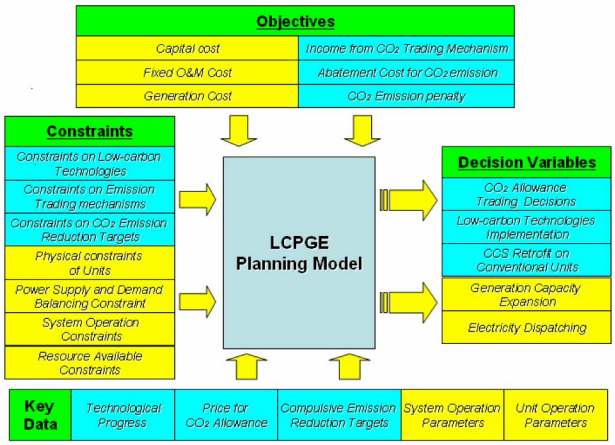

Fig. 1. Framework of the LCPGE model.

on CO_2 emission, leading to changes in production cost of electricity. Thus, the merit order of power plants in generation dispatching would be adjusted due to the differences of CO_2 intensities among plants. Secondly, CO_2 allowances might be allocated to plants freely or by auction, and the plants have to surrender allowances for their emitted CO_2; then trading mechanisms would be established for allowance transactions. These elements would affect the decisions on PGE planning. Thirdly, various low-carbon technologies would be introduced as major options to mitigate carbon emissions. Moreover, in order to restrict excessive emission, reduction obligations set in international stage and domestic compulsive reduction targets may be imposed on power sector.

The framework of LCPGE model is given in Fig. 1; shallow modules represent regular components of PGE models; and the dark ones denote the newly introduced components.

As shown in Fig. 1, the objective of LCPGE is to minimize the total cost, including not only capital investments, fixed O&M costs and generation costs, but also costs related to CO_2 emission, such as abatement costs, allowance trading incoming and emission penalty if emitting excessive CO_2. Besides capacity expansion plans and generation dispatching plans, the outputs of LCPGE model include additional decision variables on low-carbon technology implementation, CCS retrofit plans of conventional fired-based plants, and CO_2 allowance trading decisions in carbon markets. Furthermore, apart from the regular ones, constraints related to low-carbon technologies, CO_2 trading mechanisms and reduction targets are extra introduced as well.

III. Modeling Approaches

A. Discussions on the Existing PGE Modeling Approaches

There are mainly two categories of modeling approaches in PGE depending on the precise degree of modeling, which are named "micro-approach" and "macro-approach".

"Micro-approach" is utilized in [6]–[8] and [10], by which PGE models are set in mixed-integer style. "0–1" decision variables are introduced to denote the expansion options of candidate plants, which are differentiated by their types, capacities and locations. Power production simulations are adopted for generation dispatching, and evaluations on operation reliability might even be included. Meanwhile, complex constraints related to the operation of transmission network and generators are imposed. With "micro-approach", the result of PGE planning could be quite definite and fine, and the optimality of the model is always perfect if all details and data are set at high level of exactness. However, this approach is not appropriate for LCPGE as there are great uncertainties in low-carbon scenario. For example, the expectation of CO_2 emission reduction is still being discussed; the prospects of low-carbon technologies are not quite clear; and the progress of CO_2 trading mechanisms as well as carbon prices are hard to be foreseen. Therefore, it is not realistic and necessary to adopt "micro-approach" in LCPGE models, as complexities will be increased to a great extent while the improvements in precision are not equivalent.

"Macro-approach" is utilized in [9], [11] and [12]. Compared with "micro-approach", "macro-approach" is usually based on linear equilibrium, with lots of simplifications to reduce complexities of modeling. Plenty of available models based on "macro-approach" have been developed, such as MARKAL and META Net, applying "bottom-up" modeling methods. However, these models are always not established for PGE specially; most of them are applied to analyze the planning of the whole economy/energy system based on multi-sector scenarios; power plants are taken as identical elements of the models with standard definitions of inputs and outputs, like oil refinery plants in petroleum sector and vehicles in transportation sector. Key characteristics of involved activities in power sector are ignored, and the relations between PGE and power system operation are not properly considered. Therefore, PGE planning results based on "macro-approach" are always too macroscopic and roughly.

B. New Approach Developed for the Modeling of LCPGE

In order to adapt to the characteristics of LCPGE model, a new modeling approach is developed.

Firstly, capacity expansion is no longer considered unit-based. A set of power plants with the same type and location would be represented by an integrated decision variable. This scheme is referred as "plant-set-based". Thus, the integral "0-1" decision variables could be excluded. This treatment would reduce the precision of modeling to a lesser extent. Though installed capacities are of specific discrete values, they are also diversified, for example, 0.9, 1.5 and 3 MW for wind turbines. The combination of these discrete values could be taken as a continuous number approximately, especially when the total planned capacities are much more than that of any single unit.

Secondly, power production simulations are not included in LCPGE model; instead, a scheme of generation dispatching among different sets of plants is introduced. New decision variables are integrated, denoting the dispatched generation outputs to different sets of plants at a given time-scale. Generation dispatching is one of the most critical processes in determining the total generation cost and the competitiveness among different sets of plants. By adopting the scheme, plants with low production costs would be scheduled on in priority. Therefore, cost-profit features of the model could be mostly reflected.

Meanwhile, modeling works could be largely cut by avoiding the nonlinear relations within production simulations. The scheme is effective for planning cases with long time horizons and great uncertainties. Plenty of additional operation data are always required for production simulations. In scenarios with great uncertainties, it is difficult to ensure the accessibility and exactness of data. The improvements in modeling might probably be offset by the in-exactness in data obtaining. However, in the proposed scheme, the scale of required data is largely cut, while the major relations between power generation and system operation are retained. Hence, the scheme achieves a proper equilibrium between the precision of model settings and the exactness of basic data.

Moreover, as production simulation is simplified and decision variables are set "plant-set-based", it is unnecessary to consider physical connections among generators in transmission network. Instead, caps on export/import capacity between regions are introduced. In this case, constraints based on Kirchhoff Laws in power delivery could be disregarded.

With the new modeling approach, general mixed integer nonlinear PGE planning problems could be formulated as standard linear models. In this case, the augment in model scale would not largely aggravate the difficulties in finding optimal solutions. Therefore, the proposed LCPGE model is of good adaptability and could be easily expanded to deal with various new factors and more complex scenarios. It should be noted that uncertainties in low carbon factors would not be formulated by integrating probability distributions in order to better concentrate on the paper's main topic. Instead, plenty of multi-scenario analysis would be carried out in case study.

IV. Formulations of LCPGE Model

A. Decision Variables

Four groups of decision variables are presented in the model:

- $X^N_{m,y}$ expanded capacity of plant set m in year y;
- $X^R_{m,y}$ CCS Retrofit capacity of plant set m in year y;
- $X^G_{m,y}$ yearly generation dispatched to plant set m in year y;
- $X^E_{n,y}$ overall traded allowance in mechanism n in year y.

Besides, carbon prices are taken as exogenous variables by assuming perfect competition in trading mechanisms.

B. Objective Function

The scheme minimizes the aggregate of the overall cost:

$$\min C = \sum_{y\in Y}(1+r)^{-y}\left(C^I_y + C^R_y + C^O_y + C^G_y - C^E_y + C^P_y\right) \quad (1)$$

where $C^I_y, C^R_y, C^O_y, C^G_y, C^E_y$ and C^P_y. respectively. denote capital investments, CCS retrofit expenses, O&M costs, generation costs, CO_2 trading income and emission penalty in year y for the system:

$$\begin{cases} C^I_y = \sum_{m\in U} X^N_{m,y}\cdot c^I_{m,y} \\ C^R_y = \sum_{m\in U} X^R_{m,y}\cdot c^R_{m,y} \\ C^O_y = \sum_{m\in U} U_{m,y}\cdot c^O_{m,y} \\ C^G_y = \sum_{m\in U} X^G_{m,y}\cdot c^G_{m,y} \\ C^E_y = \sum_{n\in T} X^E_{n,y}\cdot\left(\pi^E_{n,y} - c^T_{n,y}\right) \\ C^P_y = E^P_y\cdot\pi^E_y \end{cases} \quad (2)$$

where $c^I_{m,y}, c^R_{m,y}, c^O_{m,y}$ and $c^G_{m,y}$ denote corresponding unit cost (per kW/kWh) according to their superscript. Y is set of all planned years; r denotes deflating rate; $\pi^E_{n,y}$ indicates CO_2 allowance price in mechanism n; $c^T_{n,y}$ denotes the related transaction cost consisting of various commissions; E^P_y represents exceeded emission allowance while π^E_y is the penalty; $U_{m,y}$ denotes the total in-service capacity of plant set m; U is set of all involved plants; and T is set of all trading mechanisms.

"Learning effect" leads to declining trend on various costs. It is treated as exogenous, constant reduction rate over time in this paper [13], [14]:

$$c^I_{m,y} = c^I_{m,0}\cdot\left(1 - r^I_m\right)^{y-y_0} \quad (3)$$

where y_0 is the starting year of planning; $c^I_{m,0}$ is the base investment in y_0; and r^I_m is the cost reduction rate in technology m. The terms in (3) could be replaced by terms related to O&M costs or production costs as well. $U_{m,y}$ is expressed as (4) at the bottom of the page.

In (4), $U_{m,0}$ is the in-service capacity of plant set m in y_0 and $U^D_{m,i}$ denotes the retired capacity. U_N is set of plants that have not been retrofitted; while U_R is set of plants retrofitted.

$$U_{m,y} = \begin{cases} U_{m,0} + \sum_{i=1}^{y} X^N_{m,i} - \sum_{i=1}^{y} X^R_{m,i} - \sum_{i=1}^{y} U^D_{m,i} & m\in U_N \\ U_{m,0} + \sum_{i=1}^{y} X^R_{m,i} - \sum_{i=1}^{y} U^D_{m,i} & m\in U_R \end{cases} \quad (4)$$

Meanwhile, E_y^P is formulated as follows:

$$E_y^P = \max\left(0, \sum_{m\in U}\left(X_{m,y}^G \cdot e_{m,y}^G\right) - \sum_{n\in T}\sum_{i=1}^{\max(Y_n^P, y-1)} X_{n,y-i}^E - E_y^T\right) \quad (5)$$

where function *max* indicates getting the bigger value within the elements in the bracket. $e_{m,y}^G$ denotes emission intensity of plant set m; Y_n^P is the length of validity period for allowance contracts; and E_y^T is cap on allowances allocated to the system, which might be decided by the government.

C. Constraints

1) Bounds on Yearly Power Generations of Plants: Year is used as a critical timescale in PGE models with long time horizons. A conception: "yearly generating hour" (YGH) is introduced to equivalently represent the utilization of power generators in average sense, which equals to annual cumulative generation outputs divided by the rated capacity of generators. Upper and lower limits should be imposed on the generation dispatching scheme:

$$H_{m,y}^L \cdot U_{m,y} \le X_{m,y}^G \le H_{m,y}^U \cdot U_{m,y} \quad (6)$$

where $H_{m,y}^U$ and $H_{m,y}^L$ is the upper and lower bounds of YGH. $H_{m,y}^U$ expressed the same meaning as capacity factors. it is always set lower than the theoretical maximum value, 8760 h, for physical issues and political issues. Though could be as low as zero when plants are not dispatched completely, $H_{m,y}^L$ is always set as special nonzero values for two reasons. Firstly, to accord with protection policies on some kinds of plants; secondly, to keep plants in-service or ready for reserve.

The introduction of CCS technology would decrease net efficiency of power plants and lead to "capacity penalty". The penalty is treated by means of discounting equivalent YGH:

$$H_{m1,y}^U = H_{m2,y}^U / \left(1 + \Delta f_y^L\right) \quad (7)$$

where $H_{m1,y}^U$ and $H_{m2,y}^U$ denote the upper limits of YGH for plants with and without CCS; and Δf_y^L denotes the loss in efficiency after implementing CCS.

2) Requirements on Available Reserve Capacities: Maintaining adequate available reserve capacities could help to mitigate the risk of unplanned outage and fluctuations in power outputs. Therefore, at the timescale of year, proper headroom of average YGH should be kept:

$$H_y^A \cdot \sum_{m\in U} U_{m,y} \ge D_y \quad (8)$$

where D_y is power demand in year y; H_y^A is the maximum average YGH for all plants involved; H_y^A is related to power mix, and could be fixed according to historical statistics.

3) Caps on Export and Import Capacities Between Regions:

$$D_{r,y} - \mathrm{Im}_{r,y} + \mathrm{Ex}_{r,y} \le \sum_{m\in Reg} X_{m,y}^G \quad (9)$$

where $D_{r,y}$ represents power demand of region r in year y; $\mathrm{Ex}_{r,y}$ and $\mathrm{Im}_{r,y}$ denotes the caps of exporting and importing capacities, which are fixed according to the total available transmission capacities between regions. Reg is set of all involved regions.

4) Equation on Power Demand and Supply: Electricity that generated by plants should be equal to the anticipated power demand annually, which is

$$\sum_{m\in U} X_{m,y}^G = D_y. \quad (10)$$

5) Limits on Cumulative Capacities: Cumulative capacities for every set of plants should be nonnegative, indicating that annual retrofitted capacities should not surpass the sum of existing and newly expanded capacities:

$$U_{m,y} \ge 0. \quad (11)$$

The expression of $U_{m,y}$ is given in (4).

6) Maximum Domestic Fuel Supply and Import Proportion: Fuel consumption should not exceed the maximum domestic production to a certain proportion for the purpose of ensuring energy supply security and reducing price risks:

$$\sum_{m\in F_n}\left(X_{m,y}^G \cdot f_{m,y}\right) \le (1 + r_{n,y}) \cdot F_{n,y}^L \quad (12)$$

where $f_{m,y}$ is fuel consumption intensity of plant set m; $F_{n,y}^L$ is the maximum available domestic production of fuel n; $r_{n,y}$ is the maximum import proportion; and F_n is set of all plants based on fuel n.

7) Caps on Exploitable Capacity: Hydro, wind and other renewable generations are not fuel-based. However, caps should also be imposed on their annual exploitable capacities, which may come from the maximum scale of available natural resources, inadequacy of technology development, or maximum production ability of equipments:

$$U_{j,0} + \sum_{i=1}^{y}\sum_{m\in R_j} X_{m,i}^N \le \sum_{i=1}^{y} R_{j,i}^L \quad (13)$$

where $R_{j,i}^L$ is caps of exploitable capacity for resource j in year i; R_j is set of plants based on resource j; and $U_{j,0}$ is the current in-service capacity of plants based on resource j.

8) First-Introduction Date of Technology: New technology would be available for commercial utilization after a specific introduction date, so we have

$$X_{m,y}^N = 0 \quad \forall y \le Y_m^A \quad (14)$$

where Y_m^A is the first introduction date of technology m.

9) Caps on Expansion Capacity in Transition Period: Transition period of new technologies indicates a specific length of

time after their first introduction dates, which always takes several years. In the transition period, caps are imposed on the expansion capacities, allowing for necessary time before the technologies could be utilized at large-scale:

$$X^N_{m,y} \le \mathrm{Cap}^{\max}_{m,y} \quad \forall Y^A_m \le y \le Y^A_m + Y^T_m. \tag{15}$$

$\mathrm{Cap}^{\max}_{m,y}$ is the cap and Y^T_m is the length of the period.

10) Constraints on CO_2 Emission: Three kinds of constraints could be imposed on total CO_2 emission, emission intensity, or reduction rate, respectively. Considering allowance trading, the constraints are expressed as (16) at the bottom of the page, where E^T is the upper bound of total emission for the whole planning period; e^T_y is the targeted emission intensive, E^T_0 is the emission level in benchmark year, r^E_y is the reduction rate; and Y_E is set of years on which r^E_y is imposed.

11) Caps on Overall Tradable Allowance in CO_2 Trading Mechanisms: Caps should be imposed on tradable CO_2 allowance when they should be real delivered in trading mechanisms, for example, in clean development mechanism (CDM). It means that the maximum traded volume could not surpass the in-hand available allowances. The constraints are imposed on the planned system, but not any single power plant or corporation:

$$X^E_{m,y} \le \sum_{m \in T_C} p^{\max}_{m,y} \cdot X^G_{m,y} \cdot \left(e^G_{m,y} - e^B_{m,y}\right) \tag{17}$$

where $e^B_{m,y}$ is the benchmark of emission intensity; T_C is set of plants qualified in mechanisms. $p^{\max}_{m,y}$ denotes the maximum tradable proportion within all qualified allowances, which is decided by size and fluidity of carbon market.

12) Constraints on Fluctuations of Yearly Expanded Capacity: The process of capacity expansion should not fluctuate violently over years in order to keep a relatively steady money flow of the planners, especially when the models are built at country-wide level. r^I is set as fluctuation rate of expanded capacity between years. The constraint could be expressed as

$$(1 - r^I) \cdot \sum_{m \in U} X^N_{m,y-1} \le \sum_{m \in U} X^N_{m,y} \le (1 + r^I) \cdot \sum_{m \in U} X^N_{m,y-1}. \tag{18}$$

13) Nonnegativity of Some Decision Variables:

$$X^N_{m,y}, X^R_{m,y}, X^G_{m,y} \ge 0. \tag{19}$$

TABLE I
CAPACITY EXPANSION PLANS OF NON-DECISIVE TYPES OF PLANTS

Plant type (in GW)	2010	2020	2030
Conventional coal-fired	420	364	280
Gas-fired	23	50	80
Oil-fired	10	12	15
Hydro	194	328	430
Nuclear	10.5	70	140
Other renewables	2	10	30

In the case study, the basic settings above would be referred as "normal scenario".

V. CASE STUDY ON CHINA'S POWER SECTOR

Being a standard linear programming problem, the LCPGE model can be solved by using some software packages, such as MATLAB, Lingo, Xpress, etc. The case model is solved by MATLAB on a Notebook with Pentium-M (2.0 GHz) processor and 1G MB of DDR-RAM.

The model is implemented to gain insights into the optimal PGE plan for China's power sector and reveal the prospects of related CO_2 emission covering a time frame from 2011 to 2030. PGE up to 2010 is not decided as most of the candidate plants for that period have already been committed. The case is established at country-wide level, regardless of multi-regions.

A. Low-Carbon Factors

1) Candidate Power Plants: Three options of coal technologies are applied: super-critical (SC), ultra-supercritical (UC), and IGCC. CCS is included as well; however, there should be a considerable period of time before CCS could be commercialized at large scale. In order to avoid "carbon lock-in" effect, being carbon capture ready (CCR) becomes an important option for normal fired-based plants. Carbon capture plants could be built directly; or be CCR first, then retrofit. Moreover, wind is included as a typical option of renewables, ignoring others.

Expansion of oil-fired (OP) and gas-fired (GP) plants are not included as decision variables, as they just account for small proportions and China lacks oil and gas resources. Hydro and nuclear are not included as well, since their long-term expansion plans have almost been set by the government. it is not realistic to incorporate too many changes on them.

2) Trading Mechanisms Involved: CDM and emission trading (ET) are included as major carbon trading mechanisms. Assuming that China would commit to reduce CO_2 emission in 2020, then CDM is the only active mechanism before 2020, and

$$\begin{cases} \displaystyle\sum_{y \in Y} \sum_{m \in U} \left(X^G_{m,y} \cdot e^G_{m,y}\right) - \sum_{n \in T} \sum_{i=1}^{\max(Y^P_n, y-1)} X^E_{n,y-i} \le E^T \\ \displaystyle\sum_{m \in U} \left(X^G_{m,y} \cdot e^G_{m,y}\right) - \sum_{n \in T} \sum_{i=1}^{\max(Y^P_n, y-1)} X^E_{n,y-i} \le D_y \cdot e^T_y \qquad y \in Y_E \\ \displaystyle\sum_{m \in U} \left(X^G_{m,y} \cdot e^G_{m,y}\right) - \sum_{n \in T} \sum_{i=1}^{\max(Y^P_n, y-1)} X^E_{n,y-i} \le E^T_0 \left(1 - r^E_y\right) \quad y \in Y_E \end{cases} \tag{16}$$

TABLE II
TECHNOLOGY COST AND PERFORMANCE DATA

Technology	Efficiency (in %)			Capital cost($/kw)			Fixed O&M cost($/kw)			Production cost($/MWh)			CO_2 intensity(kg/MWh)		
	2010	2020	2030	2010	2020	2030	2010	2020	2030	2010	2020	2030	2010	2020	2030
SC	43.0	*45.0*	*46.5*	522	497	472	35	33	31	21	20	19	75.0	72.0	69.0
SC & CCR	43.0	*45.0*	*46.5*	538	505	480	35	33	31	21	20	19	75.0	75.0	69.0
SC & CCS	35.0	*39.3*	*41.4*	848	692	632	58	47	43	26	23	22	9.0	8.5	8.0
SC Ret	31.6	*37.2*	*39.6*	403	231	174	60	48	43	29	25	23	10.0	9.0	8.4
SC & CCR Ret	33.5	*38.3*	*40.6*	374	209	160	57	46	43	27	24	22	9.4	8.7	8.2
UC	45.8	*48.0*	*49.5*	537	485	462	36	32	31	20	18	17	70.0	67.0	65.0
UC & CCR	45.8	*48.0*	*49.5*	552	494	469	36	32	31	20	18	17	70.0	67.0	65.0
UC & CCS	37.3	*41.6*	*43.9*	872	686	626	59	46	42	25	21	19	8.6	8.0	7.5
UC Ret	33.7	*39.1*	*42.3*	403	231	174	62	47	43	27	22	20	9.5	8.5	7.8
UC & CCR Ret	35.6	*40.4*	*43.2*	374	209	160	59	46	42	26	21	20	9.0	8.2	7.6
IGCC	40.0	*46.0*	*52.0*	1118	705	606	41	26	23	23	17	15	81.0	69.0	59.0
IGCC & CCR	40.0	*46.0*	*52.0*	1176	737	631	41	26	23	23	17	15	81.0	69.0	59.0
IGCC & CCS	36.0	*41.5*	*46.2*	1400	874	744	46	29	25	25	18	16	8.9	8.1	7.3
IGCC Ret	32.5	*39.5*	*45.8*	348	215	168	49	30	26	28	20	17	9.9	8.7	7.7
IGCC&CCR Ret	33.5	*39.9*	*45.4*	299	193	146	46	29	25	27	19	17	9.6	8.4	7.4
Wind	--	--	--	1251	923	834	37	27	25	0	0	0	0.0	0.0	0.0

ET would be introduced after 2020. In CDM, qualified plants would trade their allowances by means of long-term contracts, with ten years as fixed validity period. $p_{m,y}^{\max}$ for CDM is set 20% in 2011, then increased to 100% in 2020 gradually. Generally, emission reduction obligations would be introduced with ET; 2010 is set as the benchmark year; reduction obligation is set 0% in 2020, and 10% in 2030. $p_{m,y}^{\max}$ for ET is set 100% since its first introduction in 2020, thus the terms of allowance penalty could be ignored. Carbon price is set 10 $/ton for CDM and 15 $/ton for ET. Growth rate for the prices are 3%, the same as deflating rate. All the cost/price data in this paper have been converted to present values by the deflating rate.

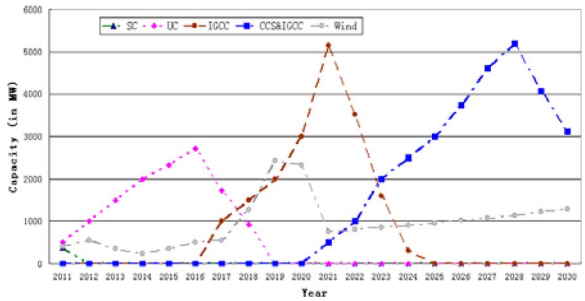

Fig. 2. Capacity expansion plan from 2011 to 2030.

B. Basic Data

Power demand in 2010 is 3430 TWh, with annual growth rate as 3.1% on average [15]. Installed capacity in 2010 is 920 GW with 681 GW fired-based, 194 GW hydro-based, 30 GW wind and 13 GW nuclear. Considering retirement schedule of existing plants and the government's agenda of "closing down small thermal power plants", 288 GW of fired-based capacity will be out of service until 2030, taking up about 42.3%.

Data on most of the candidate plant sets are presented in Table II [15]–[20]. It should be noted that some of the data are referenced by investigations with engineers in industry; and some are obtained in informal reports of demonstration projects. The cost data referenced by international experiences have been adjusted according to price differences between countries. Cost for CO_2 transportation and storage is set as 5.9 $/ton. Upper and lower bounds of YGH for SC, UC and IGCC are set 8000 and 2000 h; while for conventional coal-fired plants, the upper bounds would decline from 6000 to 2000 h gradually, embodying the government's policies of "low-efficiency power plants replacement". Cap on primary coal for generation is set 1.3 Gt in 2010, with an average annual growth rate of 3%, and the cap of import proportion is 10%. Maximum exploitable capacities for wind are 30, 120 and 220 GW in 2010, 2020 and 2030. Besides, capacity expansion plans of other sets of plants are decided according to China's 11th and 12th Five-Year Plan as well as Long-Term Developing Plan of Economy, which could be seen in Table I. IGCC and CCS would be commercialized after 2015 and 2020, with five-year transition periods [21]. The maximum fluctuation rate for expanded capacities between years is set as 20%.

In the case study, the basic settings above would be referred as "normal scenario".

C. Results and Discussions

1) Generation Capacity Expansion Plan: Fig. 2 shows the plan of PGE from 2011 to 2030. Wind is always competitive during the planning period due to its advantages in low cost and cleanness. Before 2016, UC is the first choice for expansion; however, from 2017 ~2020, regular IGCC takes the lead and the expansion of UC is going down; then declining trend could be observed on regular IGCC after 2020, when CCS begins to be available and largely developed.

The evolution of power mix is shown in Fig. 3. Remarkable reduction could be observed on conventional coal-fired plants, from 43% to 17%; SC shows a declining trend as well, though

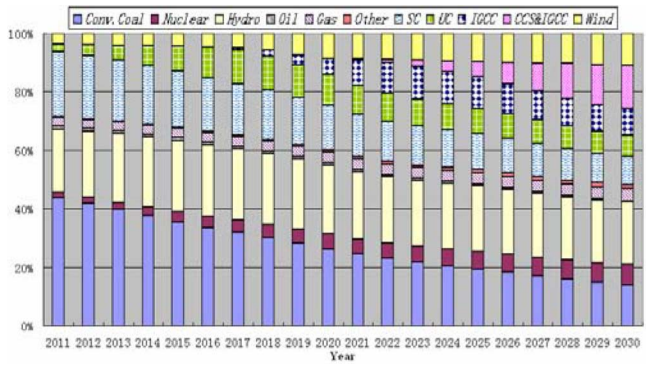

Fig. 3. Capacity proportion for different types of plants.

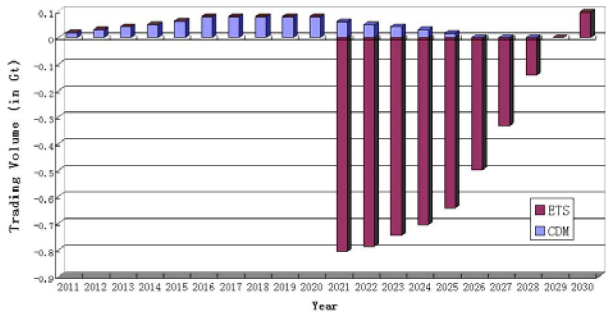

Fig. 4. CO_2 trading strategies.

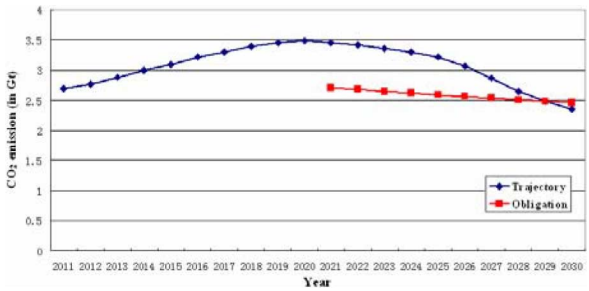

Fig. 5. CO_2 emission trajectory.

much slower. The proportions of wind and UC grow rapidly in the first few years, then wind keeps steady and UC begins to decrease after 2016. Afterward, IGCC begins to show its critical role in PGE; the proportion grows rapidly from 0% to 23%, including 13.6% with CCS and 9.4% without CCS.

2) CO_2 Trading Strategies: Fig. 4 shows the overall trading allowances in CDM and ET. Volumes in CDM increase until 2017, and start decreasing after 2020, when ET is ready. In fact, no more new CDM contracts are signed after 2020 with the occurrences of allowance shortfall; the remaining sold volumes in CDM after 2020 are from the execution of the signed contracts before 2020. The allowance shortfall is huge under the set reduction obligations, leading to great economic losses to China's power sector. Total allowance sold in CDM is 8.0 Gt, while that bought in ET is 45.6 Gt. The results indicate serious prospects of CO_2 reduction that confronted by China.

3) CO_2 Emission Trajectory: Curves in Fig. 5 depict CO_2 emission trajectory regardless of traded allowances, and the set reduction obligations. Peak emission would hit the height of

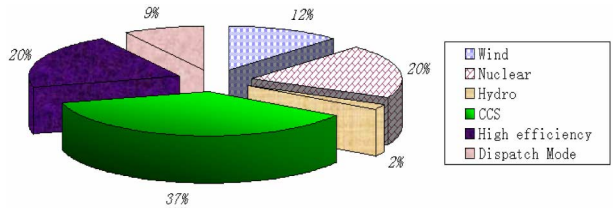

Fig. 6. Contributors of CO_2 emission reduction.

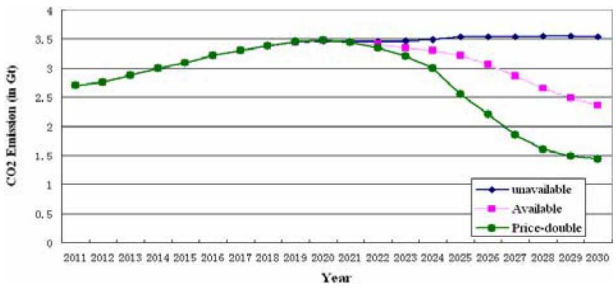

Fig. 7. CO_2 trajectories in different scenarios for CCS.

3.48 Gt in 2020, far beyond the expected obligation; and finally drop to 2.36 Gt in 2030, which is 14.5% below the base level in 2010. However, the obligations could finally be met after 2029.

4) Contributors of CO_2 Emission Reduction: Emission intensity in 2010 is 0.64 kg/kwh. If the same intensity is kept, the emission in 2030 would be 5.21 Gt. However, by adopting various mitigation actions, 2.85 Gt has been cut, which accounts for about 55%. The reduction is mainly due to the contributors listed in Fig. 6. CCS contributes about 1/3; the changing in power mix, including nuclear, wind and hydro, contributes almost another 1/3. Improvements in generation efficiency take up 20%, while the remaining 9% is from the changing of dispatching mode (by adopting the scheme in which plants with lower production costs would be scheduled on in priority, instead of the traditional scheme based on average dispatching).

5) Penetration of CCS: CCS is the most promising option for CO_2 abatement. Two extreme conditions are studied to reveal the potential of CCS and its impacts on emission trajectory, which is shown in Fig. 7. Firstly, If CCS would be unavailable during the whole planning period; no evidence of reduction could be expected, with total emission as 66.4 Gt and 3.54 Gt in 2030, increased by 7.5% and 33.3% compared with the normal scenario. Then, if carbon price is doubled, 497 GW of carbon capture plants would be installed, taking up 23.3% in power mix; however, the numbers are 219 GW and 10.9% in the normal scenario. CO_2 emission is significantly cut as well, which would be as low as 55.4 Gt totally and 1.43 Gt in 2030, decreased by 10% and 40%. The analysis above provides a rough estimation on upper and lower bounds of CCS penetration and corresponding emission trajectories.

6) Discussions on CO_2 Reduction Obligation: Reduction obligation is a "soft" scheme, with carbon price as penalty for excessive emission. With the set obligations, total expense in CDM and ET is as much as 67.1 G $. However, the losses could be significantly cut or even turned over with the delaying of the first enforcing year of reduction obligations, which could be seen in Fig. 8.

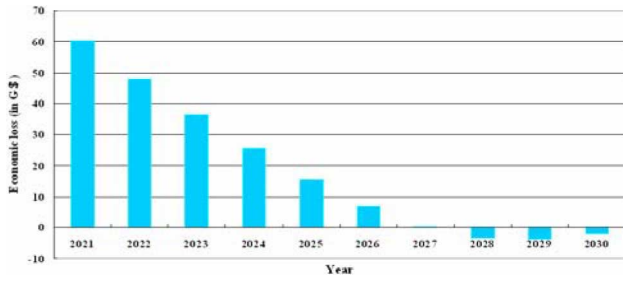

Fig. 8. CO_2 trading expenses with different first enforcing year.

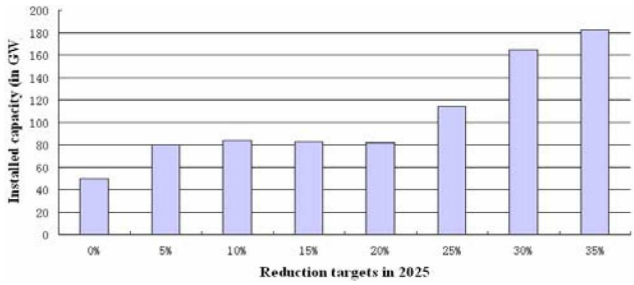

Fig. 9. Capacity of CCR and CCS retrofit under different reduction targets.

7) Discussions on CCR and Plant Retrofit: CCR and CCS retrofit are seldom utilized in the normal scenario. However, if the imposed year of reduction targets is advanced (for example, 2025 instead of 2030, as seen in Fig. 9), the direct utilization of CCS would not be "timely" enough. Hence, plenty of in-service plants should be treated as CCR first; then after CCS technologies become technical and commercial mature, large-scale of CCS retrofit will be enforced. The results shown in Fig. 9 imply that quick actions like CCR should be taken if quick reduction is required.

VI. Conclusion

An integrated PGE planning model toward LCPGE is proposed in this paper, which appropriately incorporates and formulates the impacts of various low-carbon factors. A compromised modeling approach is presented, adapting to the characteristics of the LCPGE model. With the approach, general mixed integer nonlinear PGE planning problems could be formulated as standard linear models, which remarkably decreases the complexities while maintains proper precision degree of modeling. The LCPGE model is implemented to gain insights into the optimal PGE plan for China's power sector. Trajectory of CO_2 emission is depicted, main contributors in emission reduction are identified, and economic tradeoffs in CO_2 abatement are evaluated.

The research in this paper is a new explore especially in the formulation of low-carbon factors in PGE model. Lots of more efforts should be made to improve the model and the modeling approach, for example, including production simulations or incorporating stochastic issues. These works would be carried out in the following research. Hopefully, the paper could provide new ideas in the research area of developing a low-carbon power sector.

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