Analysis of the Clean Development Mechanism Considering the Environmental Co-benefits of Reducing Air Pollutants in China

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Abstract: An electricity generation planning model of the six major Chinese power grids was developed based on the General Algebraic Modeling System to evaluate and analyze the CDM (clean development mechanism), including consideration of the environmental co-benefits of reductions in air pollutants (SOx, NOx, and particulate matter) achieved by advanced electricity generation technologies incorporating CCS (carbon capture and storage). An objective function was developed that included revenue from sales of electric power, total system cost, the cost of CO2 transport and storage, and emissions reduction co-benefits for SOx, NOx, and particulate matter. The objective function was minimized using an optimization model. We also developed a method for evaluating and analyzing the potential for transferring advanced power generation technologies into the Chinese power system through the CDM. We found that: (1) thermal power generation is predominant in the Chinese electricity system and will remain so for a long time; (2) advanced thermal plants are being installed as a result of the CDM, which contribute to decreasing emissions of CO2 and other air pollutants; and (3) CCS projects have significant potential to reduce substantial and sustained CO2 emissions from the Chinese power and industrial sectors.

Key words: Generation planning model, carbon capture and storage, co-benefits, advanced power generation, CDM activities.

1. Introduction

With nearly 10% annual economic growth over the past two decades, China has become the world’s second largest energy consuming country [1]. With domestic energy generation accounting for 70% of the energy demand, coal plays the most important role in China’s energy strategy, particularly in the electricity sector [1, 2]. While economic achievements have been substantial, exploration and low-efficiency use of large amounts of coal in electricity generation have also resulted in serious challenges, such as resource depletion and environmental degradation. SOx (sulfur oxides), NOx (nitrogen oxides), PM (particulate matter), and CO2 (carbon dioxide) are emitted by direct combustion of coal, with few emissions controls. China is now the world’s largest SO2 emitter and the second largest CO2 emitter. There are many ways to reduce CO2 emissions, including CCS (carbon capture and storage), a promising technology that can dramatically reduce CO2 emissions from consumption of fossil fuels [3-7]. CCS has the potential to capture and store CO2 from point sources such as factories and power generation plants, thereby avoiding emissions into the atmosphere and mitigating global climate change [8, 9].

The CDM (clean development mechanism) is an important approach to reducing CO2 emissions in China. The CDM is a market-based mechanism that...
allows emissions reduction projects in developing countries to earn CERs (certified emission reductions). These CERs can be traded and sold, and used by industrialized countries to partially meet their emissions reduction targets under the Kyoto Protocol. In addition to economic investments in the host countries, the CDM also provides social and environmental benefits [10-12]. CDM projects in China, in particular, promise to generate revenue and other benefits for companies and investors from industrialized countries [13-16]. 2001 was the first year in which CDM projects were registered and by September 7, 2012, the CDM had issued 1 billion CER units [16]. CCS was included in the CDM carbon offset scheme in December 2011 [17-26]. An overview of the CDM is shown in Fig. 1.

Incorporating CCS into the CDM is necessary to mitigate CO₂ emissions, and some of the barriers to this technology have previously been discussed [27-30]. However, cost estimates for CCS in the power sector are generally above $40/t CO₂ and current CO₂ prices in the CDM are too low for deployment of CCS in the power sector.

This study investigated the effects, including the co-benefits associated with reductions in other environmental pollutants, on incorporation of CCS projects into the CDM. A LP (linear programming) model of the six major Chinese power grids was developed. We estimated the number of CERs for various CER prices through 2046, using 2006 as the base year. We first estimated the number of CERs for various CER prices and the marginal damage costs associated with the air pollutants using scenario analysis. Second, we examined the relationship between the CER price and the marginal damage cost associated with the air pollutants. Finally, CCS storage was estimated for every power grid in China.

2. Methodology

The Chinese electrical power system is currently composed of six major power grids, including the north China grid, the northeast grid, the east China grid, the central China grid, the northwest grid, and the southern China grid.

2.1 Current Status of Electricity Supply and Demand

The total installed power capacity of the six major power grids was approximately 620 GW in 2006. The largest grid is the east China grid, followed by the north China grid, and the smallest is the northwest grid. The installed capacity of the two largest power grids is > 140 GW. Thermal power generation is predominant in the north China grid, the east China grid, and the central China grid. Hydropower generation plays a more important role in the other grids. The average fuel consumption per kWh of the thermal power plants at the sending end ranged from 352 gce (10.31 MJ) for the east China grid to 387 gce (11.34 MJ) for the Northwest Grid [17, 20, 21].

In addition to enlarging the unit capacity of new generation plants and abolishing smaller coal-fired power plants (10 MW), China has also recently begun to install a few advanced power plants such as USC (ultra-supercritical) coal-fired, IGCC (integrated gasification combined cycle) coal-fired, and NGCC
(natural gas combined cycle) power plants. The power generations technologies evaluated in this study were based on the world energy outlook (Table 1) [22]. China’s electricity demand was approximately 284 billion kWh in 2006 and has been increasing about 3.3% annually on average [17].

2.2 Basic Equation

The generation planning model is a linear programming model developed using the GAMS (general algebraic modeling system). The modeling period was 2006-2046. The equation determining the baseline scenario of the model is:

$$
OBJ = \sum_s (1 + D)^s \left[ \sum_j afx(j) \times inv(j) \times \sum_X X(s, j) \right] + \sum_s afx(j) \times \left( \frac{inv(j)}{inv(j)} - inv(j) \right) \times R(s, j, f) + \left( \sum_s vom(j) - ogp \right) \times G(s, j) + \sum_s pr(s, k) \times F(s, k) + \text{tstCO}_2 + \text{capCO}_2
$$

where, $OBJ$ is the discounted total system expenditure (objective function); $s$ is the year; $D$ is the discount rate; $j$ is the type of power generation plant; $afx(j)$ is the annual expenditure of generation plant type $j$ in year $s$; $inv(j)$ is the investment cost of generation plant type $j$ in year $s$; $vom(j)$ is the operation and maintenance cost of generation plant type $j$ in year $s$; $ogp$ is the on-grid price; $G(s, j)$ is the electricity generated by generation plant type $j$ in year $s$; $pr(s, k)$ is the price of fuel $k$ in year $s$; $F(s, k)$ is the consumption of fuel $k$ by generation plant type $j$ in year $s$; $tstCO_2$ is the CO$_2$ transport and storage cost, and $\text{capCO}_2$ is the CO$_2$ capture cost [23].

2.3 Environmental Protection

It is urgent to reduce the emissions of air pollutants, including SO$_x$, NO$_x$ and PM$_x$, particularly sulfur oxide emissions. The Chinese government is strongly promoting flue-gas desulfurization of thermal power plants. As part of China’s 11th five year plan (2006-2010) [24], SO$_x$ control equipment was installed on the vast majority of Chinese coal-fired power plants. The new pollution abatement equipment combined with power generation accounted for 76 GW of the most highly polluting older coal-fired power plants, which reduced total sulfur emissions by over 14.6% in China [25]. NO$_x$ control was added in March 2011 in the 12th five year plan. According to the Chinese electricity council, by the end of 2010, 14% of the coal-fired power plants (90 GW) had installed NO$_x$ control equipment.

During the next five years, this number will grow considerably. Three types of emissions control for coal-fired power plants and two types of emissions control for natural gas power plants [17] have been developed. Moreover, emissions standards have been promulgated by the Chinese government for air pollutants (GB13223-2011) (Table 2).

2.4 Carbon Capture and Storage and Emissions Factors

2.4.1 Relationship between Carbon Capture and Storage Cost and CO$_2$ Storage

Computation of CO$_2$ transport and storage in China was performed based on the work of Dahowski et al. [23], who developed CO$_2$ transport and storage cost curves for each of the six major regions in China. These data provide a detailed look at the demand and costs of CO$_2$ storage across different parts of the country, where economic characteristics, the energy and industrial infrastructure, and the geology all contribute to varying results. These detailed cost curves highlight the unique CCS deployment potential and range of costs within each region and the relative differences in total potential annual demand for CO$_2$ storage from one region to the other. The East region has the largest number of sources and the most CO$_2$ paired with nearby prospective CO$_2$ storage formations, and the northwest has the fewest. The south central region has the widest range of transport and storage costs of $72$-$146$/tCO$_2$, compared with the north region with the narrowest, with peak costs at $35$/tCO$_2$. The CO$_2$ transport and storage cost curves used in this study are applicable to the first 20 year of the analysis period;
Table 1 Specifications for Chinese power generation technologies.

<table>
<thead>
<tr>
<th>Year</th>
<th>Investment costs ($/kW)</th>
<th>O &amp; M costs ($/kW)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2010</td>
<td>2020</td>
<td>2035 +</td>
</tr>
<tr>
<td>SUB</td>
<td>600</td>
<td>600</td>
<td>600</td>
</tr>
<tr>
<td>SC</td>
<td>700</td>
<td>700</td>
<td>700</td>
</tr>
<tr>
<td>USC</td>
<td>800</td>
<td>800</td>
<td>800</td>
</tr>
<tr>
<td>IGCC</td>
<td>1,100</td>
<td>1,100</td>
<td>900</td>
</tr>
<tr>
<td>NGCC</td>
<td>1,500</td>
<td>1,500</td>
<td>1,500</td>
</tr>
<tr>
<td>USC + CCS</td>
<td>1,000</td>
<td>1,000</td>
<td>1,000</td>
</tr>
<tr>
<td>IGCC + CCS</td>
<td>1,800</td>
<td>1,800</td>
<td>1,600</td>
</tr>
<tr>
<td>NGCC + CCS</td>
<td>2,180</td>
<td>2,110</td>
<td>2,020</td>
</tr>
<tr>
<td>Wind</td>
<td>2,590</td>
<td>1,760</td>
<td>1,360</td>
</tr>
</tbody>
</table>

Note: O & M = operation and maintenance, SUB = subcritical, SC = supercritical, USC = ultra-supercritical, IGCC = integrated gasification combined cycle, NGCC = natural gas combined cycle, USC + CCS = ultra-supercritical with CCS, IGCC + CCS = integrated gasification combined cycle with CCS, NGCC + CCS = natural gas combined cycle with CCS, and PV = photovoltaic.

Table 2 Emissions standards for air pollutants.

<table>
<thead>
<tr>
<th>Pollutants</th>
<th>Applicability</th>
<th>Limits</th>
<th>Effective date</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM</td>
<td>Newly established plants and existing plants</td>
<td>30 mg/m³</td>
<td>1/1/2012 for newly established plants</td>
</tr>
<tr>
<td>SO₂</td>
<td>Newly established plants</td>
<td>100 mg/m³</td>
<td>1/7/2014 for existing plants</td>
</tr>
<tr>
<td>NOₓ</td>
<td>Existing plants</td>
<td>200 mg/m³</td>
<td></td>
</tr>
<tr>
<td>NOₓ</td>
<td>Newly established plants and existing plants</td>
<td>100 mg/m³</td>
<td>1/7/2014 for existing plants</td>
</tr>
<tr>
<td>Gas-fired boiler NOₓ</td>
<td>Newly established plants and existing plants</td>
<td>50 mg/m³</td>
<td></td>
</tr>
</tbody>
</table>

However, the modeling period of this study is 2006-2046. Therefore, it was necessary to consider changes in the cost curves after the first 20 years.

2.4.2 Calculation of the CO₂ Storage Cost

Mathematical functions are needed to calculate the cost of CO₂ transport and storage in China. However, only cost curves currently appear in Ref. [23]. We transformed these cost curves into the functions shown below:

\[
y_1 = -\frac{1817}{63} \times x \quad (0 \leq x \leq 63) \tag{2}
\]

\[
y_2 = -\frac{1817}{1038} \times \frac{x - 63}{8863} \times (63 \leq x \leq 1101) \tag{3}
\]

\[
y_1 = -\frac{3385}{75} \times x \quad (0 \leq x \leq 75) \tag{4}
\]

\[
y_2 = -\frac{3385}{663} \times \frac{x - 75}{2626} \times (75 \leq x \leq 738) \tag{5}
\]

\[
y_1 = -\frac{4378}{100} \times \frac{x}{100} \quad (0 \leq x \leq 100) \tag{6}
\]

\[
y_2 = -4378 + \frac{1475}{196} \times (x - 100) \quad (100 \leq x \leq 296) \tag{7}
\]

\[
y_1 = -\frac{1260}{35} \times \frac{x}{35} \quad (0 \leq x \leq 35) \tag{8}
\]

\[
y_2 = -\frac{1260 + 1257.5}{155} \times \frac{x - 35}{155} \quad (35 \leq x \leq 190) \tag{9}
\]

\[
y_1 = -\frac{511}{14} \times x \quad (0 \leq x \leq 14) \tag{10}
\]

\[
y_2 = -\frac{511 + 2618}{386} \times \frac{x - 14}{386} \quad (14 \leq x \leq 400) \tag{11}
\]

\[
y_1 = -\frac{630}{28} \times x \quad (0 \leq x \leq 28) \tag{12}
\]

\[
y_2 = -\frac{630 + 1294}{192} \times \frac{x - 28}{192} \quad (28 \leq x \leq 220) \tag{13}
\]

Where, Eqs. (2) and (3) were used to calculate the cost of transport and storage in the east region, Eqs. (4) and (5) were used for the north region, Eqs. (6) and (7) for the northeast region, Eqs. (8) and (9) for the northwest region, Eqs. (10) and (11) for the south central region, and Eqs. (12) and (13) for the southwest region, x
represents the cumulative supplied annual capacity of CO₂ transport and storage (Mt CO₂) and \( y(i = 1, 2) \) is the cost of CO₂ transport and storage ($/t CO₂).

### 2.4.3 Relationship between the CO₂ Capture of the Power Grids and the Storage Region

CCS is a technology in which CO₂ is separated from industrial and energy-related sources, transported to a storage location, and isolated from the atmosphere over the long-term. CCS technology itself can also reduce some air pollutant by-products in addition to those removed by the desulfurization system (DeSO₂) and the NOₓ removal system (DeNOₓ). SO₂ and NOₓ in the flue gases are captured by the solvents used to remove the CO₂. There are six administrative regions in which CO₂ is stored that originated from the six major Chinese power grids, including the north China region, the northeast region, the east China region, the northwest region, the central south region, and the southwest region. The six administrative regions used for storage are not congruent with the six major power grids in China, i.e., some CO₂ needs to be stored in regions other than that in which it was generated. The relationships between the CO₂ emissions of the power grids and the storage regions are shown below:

\[
\text{NorthCCS} = 0.68 \times \text{airccs (north, s)} \\
\text{NortheastCCS} = \text{airccs (northeast, s)} \\
\text{NorthwestCCS} = \text{airccs (northwest, s)} \\
\text{CentralsouthCCS} = 0.713 \times \text{airccs (central, s)} + 0.67 \times \text{airccs (south, s)} \\
\text{SouthwestCCS} = 0.33 \times \text{airccs (south, s)} + 0.19 \times \text{airccs (central, s)} \\
\text{EastCCS} = \text{airccs (east, s)} + 0.32 \times \text{airccs (north, s)} + 0.097 \times \text{airccs (central, s)}
\]

where, \( \text{airccs} \) represent the CO₂ emission \( s \) of generation plants with CCS in year \( s \) in the north grid, east grid, northeast grid, northwest grid, central grid, and south grid, respectively.

To examine the additivity of the CDM, the baseline CO₂ emissions factor was determined by calculating the weighted average of two emission factors (OM (operating margin) and BM (build margin)) pertaining to the electricity system. OM refers to the group of existing power plants whose current electricity generation would be affected by the proposed CDM project activities. BM refers to the group of prospective power plants whose construction and future operation would be affected by the proposed CDM project activities. The combined margin is calculated as follows:

\[
\text{EF}_{\text{grid,s}} = \text{EF}_{\text{grid,s,OM}} \times W_{s,OM} + \text{EF}_{\text{grid,s,BM}} \times W_{s,BM}
\]

where, \( \text{EF}_{\text{grid,s}} \) is the baseline emissions factor of a power grid in the year \( s \); \( \text{EF}_{\text{grid,s,OM}} \) is the OM emissions factor of the grid in the year \( s \); \( W_{s,OM} \) is the weighting factor for OM in the year \( s \); \( \text{EF}_{\text{grid,s,BM}} \) is the BM emissions factor in the year \( s \); and \( W_{s,BM} \) is the weighting factor for BM in the year \( s \).

The emission factors for air pollutants from power plants without CDM were calculated based on the regulations promulgated by the Chinese government (GB13223-2011). The emission factors for air pollutants from CDM power plants were calculated based on data for Japanese power generation technologies. Results for the emissions factors for the air pollutants are shown in Table 3.

### 2.5 Co-benefits of Reducing Air Pollution Emissions

The authors assumed that the co-benefits attributed to a reduction in air pollutant emissions were equal to the marginal damage cost of air pollution. The marginal damage cost of air pollution was estimated using contingent valuation of marginal willingness to pay MWTP (marginal willingness to pay) to avoid impacts to human health, natural resources, and potential photo synthetic NPP (net primary productivity) based on studies conducted in three
cities in China. The marginal damage costs per ton of emissions of SO\(_x\), NO\(_x\), and PM in China in the future were estimated using the following formulas [31-33]:

\[
MC_{x,\text{CHN},yr} = DC_{x,\text{JPN},yr0} \times \lambda_{x,\text{CHN},yr} \times WF_{x,\text{CHN},yr}
\]

(21)

\[
WF_{x,\text{CHN},yr} = WF_{x,\text{CHN},yr0} \times \left( \frac{y_{\text{CHN},yr}}{y_{\text{CHN},yr0}} \right)^\alpha
\]

(22)

where \(x\) = the type of impact, \(yr0\) = the base year (2010), \(yr\) = year, \(MC_{x,\text{CHN},yr}\) = marginal damage cost per ton of air pollutant emission in China in the year \(yr\) with respect to the impact \(x\). \(DC_{x,\text{JPN},yr0}\) = risks attributed to emissions of air pollutants estimated in Japan in the base year with respect to the impact \(x\). \(\lambda_{x,\text{CHN},yr}\) is an adjustment factor. For human health impacts, this factor equals the population density of China in the year \(yr\) normalized to that of Japan in the base year. Likewise, this factor equals the GDP of China in the year \(yr\) normalized to that of Japan in the base year for natural resources impacts, and the potential net primary productivity of China in the year \(yr\) normalized to that of Japan in the base year for impacts to net primary productivity. \(WF_{x,\text{CHN},yr}\) = willingness to pay for a reduction in the risks associated with air pollution in China in the year \(yr\), \(y_{\text{CHN},yr}\) = the GDP (gross domestic product) per person in China in the year \(yr\), \(\alpha\) = the GDP elasticity of WTP. The marginal damage costs of the co-benefits per ton of reduced SO\(_x\), NO\(_x\), and PM emissions are shown in Table 4. Because there is not yet a reliable value for elasticity \(\alpha\), \(\alpha\) was conservatively assumed to be zero. A sensitivity analysis was conducted by changing the values for the co-benefits, described in Section 3.3.

### 3. Results and Discussion

The authors evaluated the impacts of including the co-benefits of reducing additional pollutants as part of the CDM on the viability of CCS with an LP model. In addition, air pollution emissions from thermal electricity generation and the number of CERs were estimated assuming various CER prices. The relationship between the CER price and the marginal damage costs of the air pollutants was also explored.

#### 3.1 Optimization Results at Baseline

3.1.1 Annual Electricity Generation of China at Baseline

The baseline was estimated without CDM projects or the marginal damage costs of air pollutants. The annual electricity generation of China at baseline is shown in Fig. 2. The total annual electrical power generation of China increased from 2,263 TWh to 7,333 TWh from 2006 to 2046, with USC coal power generation with DeSO\(_x\) and DeNO\(_x\) becoming increasingly prevalent. Among the coal-fired power generation technologies, COAL_USC was dominant, comprising 5,432 TWh in 2046. COAL_SUB and COAL_SC power generation decreased with an increase in NGCC and NUCLR power generation. It was assumed that IGCC power generation was installed beginning in 2031, hydropower generation was installed to its maximum capacity due to low fuel costs, and nuclear generation was also installed to its maximum capacity in accordance with the Chinese nuclear power generation plan. Small coal-fired power generation decreased because small power generation plants are being gradually decommissioned. Coal-fired power generation with CCS was not included in the baseline.

#### 3.1.2 CO\(_2\), SO\(_x\), NO\(_x\) and PM Emissions

Per kWh emissions of CO\(_2\) and air pollutants from thermal power generation are shown in Figs. 3-6. Under the baseline scenario, CO\(_2\) emissions are expected
Table 4  Marginal damage costs associated with pollutants [31, 32].

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Year 2016</th>
<th>Year 2021</th>
<th>Year 2026</th>
<th>Year 2031</th>
<th>Year 2036</th>
<th>Year 2041</th>
<th>Year 2046</th>
</tr>
</thead>
<tbody>
<tr>
<td>SO(_2) ($/kg)</td>
<td>1.5</td>
<td>1.8</td>
<td>2.2</td>
<td>2.5</td>
<td>2.9</td>
<td>3.3</td>
<td>1.9</td>
</tr>
<tr>
<td>NO(_x) ($/kg)</td>
<td>1.3</td>
<td>1.6</td>
<td>1.9</td>
<td>2.2</td>
<td>2.6</td>
<td>3.0</td>
<td>3.3</td>
</tr>
<tr>
<td>PM ($/t)</td>
<td>44</td>
<td>45</td>
<td>47</td>
<td>47</td>
<td>47</td>
<td>47</td>
<td>47</td>
</tr>
</tbody>
</table>

Fig. 2  Annual electricity generation by type.

to decrease annually, as a result of the advanced electricity generation technologies that have been installed in China with lower emissions of CO\(_2\). We found that emissions of SO\(_x\) and NO\(_x\) will be substantially reduced from 2011 to 2016 due to the emissions standards for SO\(_x\) and NO\(_x\) promulgated by the Chinese government.

3.2 Optimization Results for Clean Development Mechanism Projects

3.2.1 Additional Equations for Clean Development Mechanism Evaluation

Eqs. (11)-(14) were combined with Eq. (1) to evaluate CDM activities. We assumed that construction and operation of so-called “must-run” power plants (nuclear, hydro, and wind) would not be influenced by CDM activities [34].

3.2.2 Certified Emission Reductions Relationship

The number of CERs earned is determined by comparing the CO\(_2\) emissions per kWh of a CDM project with the average CO\(_2\) emissions per kWh for all thermal power plants other than small coal-fired power plants:

\[
CER (x) = (1 - shpr) \sum_{y \in \text{other}} G(x, y) \{ \text{emissions} (x, CO_2) \} - \sum_{y \in \text{other}} \{ \text{emissions} (y, CO_2) \} \text{ret}(y, CO_2) \text{gen}(y, k) \}
\]

(11)
where $shrp$ is the share of the profit. CERs are obtainable only during the crediting period of the CDM project. The share of the profit was assumed to be 0.02 and the length of the crediting period 10 yr.

3.2.3 Additivity Relationship

Suppose that a CDM project is begun in the year $s$. Eq. (12) represents the internal rate of return of the CDM project, which is $< 0$. In contrast, Eq. (13) represents the internal rate of return of the CDM project with the sale of the associated CERs, which is now $\geq 0$:

$$\sum_{j \in CDM}(1 + A)^{-s}[– afx(j)inv(j)X(s’, j) + \phi_{dpg} - vam(j) - \sum_k pr(s,k)gef(k,j)G(s,j)] \leq 0$$

$$\sum_{j \in CDM}(1 + A)^{-s}[– afx(j)inv(j)X(s’, j) + \phi_{dpg} - vam(j) - \sum_k pr(s,k)gef(k,j)G(s,j) + \sum_k \phi_{pcer} \cdot \text{CER}(s)] \geq 0$$

where, $A$ is the threshold value for the internal rate of return for the CDM project, $gef(k, j)$ is the consumption of fuel $k$ per kWh by generation plant type $j$, $pcer$ is the price of a CER, and $\text{CER}(s)$ is the number of CER emissions credits earned in year $s$. CERs are accumulated only during the crediting period. The value of $A$ was assumed to be 0.08.

3.2.4 Emissions Reduction Relationship

Eq. (14) ensures that emissions of air pollutants by the CDM project are reduced below the baseline level:

$$\sum_{j \in CDM} G(s, j) \cdot \text{som}(s, env) - \sum_k ef(k, env) \cdot rd(j, env) \cdot gef(j, k) \geq 0$$

where, $G(s, j)$ is the electricity generated by generation plant type $j$ in year $s$, $\text{som}(s, env)$ is the average baseline emissions of pollutant $env$ per kWh in year $s$ of all thermal power plants other than small coal-fired power plants, $env$ is the air pollutant, $ef(k, env)$ is the emissions of pollutant $env$ per heat content of fuel $k$, $rd(j, env)$ is the reduction in the emissions of $env$ by generation plant type $j$. $E(s, env)$ is the emissions of pollutant $env$ in year $s$, $ebl(s, env)$ is the baseline emissions of pollutant $env$ in year $s$.

3.2.5 New Objective Function

Eq. (15) defines the objective function of the optimization model with CDM projects, which replaces Eq. (1) used in the baseline case [26, 30]. Eq. (15) includes the revenue from sales of CERs, counted only during the crediting period:

$$\text{Newobj} = \sum_{s} (1 + D)^{-s} \left[ \sum_{j \in CDM} afx(j) \cdot inv(j) \cdot X(s’, j) + \sum_{j \in CDM} vam(j) \cdot R(s, j, j’) + \sum_{s} pr(s, k) \cdot F(s, k) + tscCO_{2} + \text{capCO}_{2} - \text{pcer} \cdot \text{CER}(s) - \text{csox} \cdot \text{SO}_{x}(s) - \text{cnox} \cdot \text{NO}_{x}(s) - \text{cpm} \cdot \text{PM}(s) \right]$$

where, $csox$ is the marginal damage cost of $SO_{x}$; $\text{SO}_{x}(s)$ is the reduction in emissions of $SO_{x}$ due to the CDM projects in year $s$; $cnox$ is the marginal damage cost of $NO_{x}$; $\text{NO}_{x}(s)$ is the reduction in emissions of $NO_{x}$ due to the CDM projects in year $s$; $cpm$ is the marginal damage cost of $PM$; and $PM(s)$ is the reduction in emissions of $PM$ due to the CDM projects in year $s$.

3.3 Results for Clean Development Mechanism Potential

There are several factors that influence the potential of CDM, including the CER price, fuel price, on-grid price, length of the crediting period, environmental standards, etc.. In this study, CDM_USC, CDM_USC_CCS, CDM_IGCC, CDM_IGCC_CCS,
CDM_NGCC, and CDM_NGCC_CCS projects were assumed to be initiated in 2016. In addition, the crediting period for a CDM project was assumed to be 10 years and the on-grid price was assumed to be 0.40 rmb/kWh.

To clarify the relationship between the CER price and the marginal damage costs of the air pollutants, a sensitivity analysis was conducted. Five alternative values for the co-benefits associated with SOx, NOx, and PM were used: 0%, 50%, 100%, 150%, and 300% of the co-benefits shown in Table 3. The number of CERS under these scenarios and with varying CER prices for CDM_IGCC and CDM_NGCC is shown in Figs. 7 and 8, respectively, assuming implementation in 2016. For CDM_IGCC, which is beginning to be introduced in the Northwest Grid at a lower CER price of $40/t CO2, there is a marked difference between the scenarios with and without co-benefits. When the CER price increases to $80/t CO2, the case for co-benefits substantially improves. Moreover, the number of CERS conspicuously increases with an increase in co-benefits.

For CDM_NGCC, although the number of CERS is similar whether or not co-benefits are included, the total number of CERS is much larger than for CDM_IGCC. Comparison of the two technologies implemented in 2016 indicates that CDM_IGCC is much more sensitive to inclusion of co-benefits.

The number of CERS earned for USC plants with CCS by CDM projects implemented in 2016 with varying CER prices is shown in Fig. 9. CERS begin to be earned when CDM_USC_CCS is installed at a CER price of $20/t CO2 with co-benefits, but are not earned at that price without co-benefits. At or above a CER...
price of $25/t CO₂, the number of CERs earned is nearly the same with or without co-benefits until the CER price increases to $80/t CO₂. However, there is a substantial increase in the number of CERs with increased levels of co-benefits.

The number of CERs earned for NGCC plants with CCS by CDM projects implemented in 2016 with varying CER prices is shown in Fig. 10. CERs begin to be earned when projects are installed at a CER price of $65/t CO₂ in the North West Grid and the number of CERs earned increases with the CER price. The number of CERs is similar whether or not co-benefits are included when the CER price is $75-80/t CO₂; however, more CERs are earned with co-benefits than without above this price. In addition, there is a substantial increase with higher levels of co-benefits when the CER price is $65-5/t CO₂.

For USC plants with CCS for CDM projects installed in 2016, Fig. 11 shows CO₂ storage in the Northwest Grid and North Grid with and without co-benefits, respectively. CO₂ begins to be stored when the CER price is $20/t CO₂ in the Northwest Grid. With co-benefits, the amount of CO₂ storage is larger in the north grid because storage is less expensive there. Without co-benefits, CO₂ begins to be stored in the northwest grid when the CER price is $25/t CO₂.

For NGCC plants with CCS for CDM projects installed in 2016, Fig. 12 shows CO₂ storage in the South Grid with and without co-benefits. With co-benefits, CO₂ begins to be stored when the CER price is $65/t CO₂, while without co-benefits, CO₂ begins to be stored when the CER price is $70/t CO₂. The level of storage is the same with and without co-benefits when the CER price is $75/t CO₂; however, with co-benefits, CO₂ storage with co-benefits is greater than that without above a CER price of $75/t CO₂.
Based on these results, environmental co-benefits have a positive impact on CDM potential and on storage of CO₂ associated with CCS. Based on the results of Figs. 7-10, two additional trends were observed.

First, co-benefits have a stronger impact on CDM projects, particularly on IGCC power generation. This is likely because the power efficiency difference between CDM_IGCC plants and conventional coal power plants is smaller than that between CDM_NGCC plants and conventional coal power plants. Smaller differences in power efficiency result in a larger effect of co-benefits on CERs/kWh of electricity supplied by a CDM power plant. For power generation with CCS, the effects of co-benefits on CERs/kWh are smaller compared with power generation without CCS, because in the latter case, only 10% of the CO₂ is released into the air. Thus, the effects of co-benefits for NGCC with CCS are relatively small.

Second, there are regional differences depending on the cost of fuel and CO₂ transport and storage. IGCC CDM power plants without CCS in the Northwest Grid and North Grid are more prevalent than in other regions because the coal price is much lower in these areas. CDM_NGCC plants without CCS have the greatest potential in the South China Grid, where coal prices are the highest among all the power grids and consequently, natural gas is relatively inexpensive. On the other hand, there are more CDM_USC power plants with CCS in the North region than in other regions because CO₂ transport and storage is much less expensive in that region. There are also more CDM_NGCC power plants with CCS in the South Central Grid because the price of natural gas is lower than in other regions.

4. Conclusions

A generation planning model of the six major Chinese power grids was developed and used to evaluate and analyze the potential for transferring advanced power generation technologies into the Chinese power system as CDM activities, considering the environmental co-benefits of reducing emissions of air pollutants (SOₓ, NOₓ and PM) through advanced electricity generation technology. Based on the modeling results, several conclusions were reached.

First, the growing Chinese economy strongly depends on use of coal and this will remain the case for some time. Because of the low price and abundant resources of coal in the electricity sector, the demand for conventional coal generation will substantially increase and dominate the thermal electricity sector along with economic growth for the foreseeable future. In the baseline scenario, USC power generation is projected to become dominant, with annual electricity generation greater than that of IGCC, in part because IGCC power generation with CCS has not yet been introduced.

Second, advanced thermal plants are being installed as CDM projects in developing countries, contributing to decreasing CO₂ emissions as well as other air pollutants. CERs earned from CDM projects are projected to be greatest in grids where IGCC is installed, when co-benefits are included. IGCC significantly contributes to reducing SOₓ and NOₓ emissions along with CO₂ emissions. Although reductions in SOₓ, NOₓ and PM emissions are proportionately greater than reductions in CO₂ emissions, the total amount of CO₂ emissions reduced is larger because CO₂ emissions are so much greater than SOₓ, NOₓ and PM emissions. As a result, when IGCC is installed through CDM projects, SOₓ and NOₓ reduction benefits tend to be larger. We found that advanced power generation technologies have environmental advantages other than CO₂ emissions reduction; thus, it is important that the environmental co-benefits of technology transfer through CDM projects are examined.

Third, the market for clean energy technologies is strong world-wide, particularly in China, where the rapid growth rate and heavy reliance on coal provide substantial opportunities for deployment of new
technologies. We also evaluated the potential of CO₂ CCS in CDM projects, including assessment of the CCS potential of the six major power grids in China. The results of this study revealed that there is significant potential for CCS to offer deep and sustained CO₂ emissions reductions from the Chinese power and industrial sectors.

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