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# Emissions trading and abatement cost savings: An estimation of China's thermal power industry

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**Abstract:** This study evaluates the efficiency advantage of a market-based emission permit trading policy instrument over a command and control policy instrument in the case of China's thermal power industry. We estimate the unrealized gains achievable through emission permit trading with an optimization frontier analysis. These unrealized gains include potential recoveries of electricity generation through eliminating spatial and temporal regulatory rigidity on emission permit trading. The results of an ex post estimation during 2006 and 2010 indicate a potential gain of 8.48% increase in electricity generation if both the intra- and inter-period regulatory rigidities $CO_2$ emission permits trading had been eliminated. In addition, if the permit trading systems for three air pollutions, $CO_2$, $SO_2$, and $NO_x$, had been completely integrated, a positive net synergy effect of 1.43% increase in electricity generation could have been secured. The unrealized gains identified in this study provide supports for establishing a nationwide emission permit trading system in China.

**Keywords:** Data envelopment analysis; $CO_2$ emissions; Regulatory rigidity; Synergy effect; Tradable permits

## 1 Introduction

As the world's largest emitter of greenhouse gases, China has recently (November 12, 2014) announced in the China-US climate change agreement that it "intends to achieve the peaking of $CO_2$ emissions around 2030 and to make best efforts to peak early" (The White House, 2014). This agreement reveals China's post-2020 action on climate change mitigation which is also seen as the successor to China's announcement at the 2009 Copenhagen climate change summit of its intention to reduce its $CO_2$ emission intensity (carbon emissions per unit of GDP) by 40 to 45 percent from the 2005 level by 2020. In order to achieve this emission control target, China implemented a series regulations and policies on energy saving and $CO_2$ emission reduction during the 11th and 12th Five-Year Plan (FYP) periods (2006-2010 and 2011-2015 respectively). At the national level, the energy intensity (energy consumption per unit of GDP) reduction targets were respectively assigned as 20% (from the 2005 level by 2010) and 16% (from the 2010 level by 2015), and the $CO_2$ emission intensity reduction target was assigned as 17% from the 2006 level by 2015. In addition, during the 11th and 12th FYP periods, regulations were also put in place to reduce emissions of sulfur dioxide ($SO_2$) and nitrogen oxide ($NO_x$) by 8-10% (SCC, 2007; SCC, 2011). These national targets were further disaggregated at regional level for China's provincial regions and were taken as their mandatory regulations to constrain the environmental externalities of energy consumption and economic development.

The thermal power industry contributed more than 40 percent of global $CO_2$ emissions in 2010 (IEA, 2011). This percentage is even higher in China as thermal electricity generation accounts for approximately 50 percent of China's total coal consumption[*], as well as being responsible for more than 40 percent of $CO_2$ emissions from fuel combustion and approximately 50 percent of the total $SO_2$ emissions in China[†]. At the same time, the thermal power industry generates approximately 80 percent of China's total electricity[‡]. Therefore, the thermal power sector plays a crucial role in China's efforts to control $CO_2$ emissions and reduce air pollutants (Zhao et al., 2015; Lin and Yang, 2013).

From the beginning of the 11th FYP period, China implemented various policy instruments to achieve the joint target of economic growth and emission reduction. These policy instruments included command and control policies and market-based policies. National $CO_2$ emission intensity reduction target and associated mandatory emission reduction schemes were proposed in the 11th and 12th Five-year Comprehensive Work Plans for Energy Conservation and Emission Reduction (SCC, 2007; SCC, 2011). In addition, thermal power-related $SO_2$ and $NO_x$ emission reduction targets (16% and 29% respectively from the 2010 levels by 2015) and associated mandatory emission reduction schemes proposed specifically in the 12th Five-Year Plan for Energy Conservation and Emissions Reduction (SCC, 2012) were command and control policy instruments used to implement major plans in the last decade. However, the market-based policy instruments such as emission permit trading have only recently been implemented. Starting in June 2013, China launched seven successive pilot markets for greenhouse gas emission permit trading in Shenzhen (June 2013),

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[*] According to the China Energy Statistical Yearbook, in 2010, China’s total coal consumption was 3122 million tonnes and total coal consumption in thermal power industry was 1663 tonnes.

[†] In 2010, China’s total $CO_2$ emissions from fuel consumption and cement production were 8288 million tonnes (Oak Ridge National Laboratory, 2011), and, according to our estimation, the $CO_2$ emissions from thermal electricity generation were 3130 million tonnes. According to the Annual Statistical Report on the Environment in China, in 2010, China’s total industrial $SO_2$ emissions were 18644 thousand tonnes and total $SO_2$ emissions from thermal electricity generation were 8347 thousand tonnes.

[‡] China’s total electricity generation and total thermal electricity generation in 2010 were 4207 and 3417 billion kWh, respectively.

Shanghai (November 2013), Beijing (November 2013), Guangdong (December 2013), Tianjin (December 2013), Hubei (April 2014) and Chongqing (June 2014). Although, the carbon emission permit trading scheme is still at the experimental pilot stage, the total amount of greenhouse gas emission quotas of these seven pilot markets has exceed 1.2 billion tonnes of $CO_2$ equivalent, making China the second largest carbon market in the world (following the EU Emissions Trading System). In the next five years, it is intended to establish a nationwide unified greenhouse gas emission permit trading system in China based on the experiences obtained from the pilot markets.

The emission permit trading scheme is a market-based regulatory strategy for achieving a reduction in pollutant emission at the minimal abatement cost (Kunsch et al., 2004). The aforementioned EU Emissions Trading System established for reducing greenhouse gas emissions in Europe cost effectively and the US $SO_2$ tradable permits program, which began with the passing of the Clean Air Act in the United States, are two representative market-based policy instruments that have already been applied. Theoretically, heterogeneity in emission abatement cost determines the efficiency advantage of a market-based emission permit trading policy over a command and control policy on emission reduction (Carlson et al., 2000; Rong and Lahdelma, 2007), and this efficiency advantage can be identified by estimating the unrealized gains that can be obtained from emission permit trading. The unrealized gains represent the potential recoveries on desirable output loss (caused by emission abatement activities) through implementing an emission permit trading policy instead of a command and control policy. Furthermore, the unrealized gains can also be seen as the savings on emission abatement costs when emission permits are tradable.

This study attempts to discover whether there are unrealized gains and if so, how much the unrealized gains in China's thermal power industry would be if $CO_2$ emissions and other pollutant emissions from thermal electricity generation were tradable. The estimation of unrealized gains can help to identify the savings on abatement costs from emission permit trading and thus provide primary arguments for introducing an emission permit trading scheme and establishing a national emission permit trading system in China, particularly for the thermal power industry.

Several previous studies have attempted to estimate the unrealized gains or potential gains from emission permit trading. Brännlund et al. (1998) estimated the profit from emission (biological and chemical oxygen demand and suspended solids) permit trading in the Swedish pulp and paper industry by developing models with and without potential emission trading regimes. The industry profit difference between these two regimes was then taken as an estimate of potential gains that could be realized by allowing for emission permit trading. Their study revealed that the profits of this industry would be 1-6 percent higher in 1989-1990 if an emission trading regime had been used instead of a command and control regime. Färe et al. (2013) calculated the potential increase in electricity generation of US coal-fired electric power plants if the existing tradable permit ($SO_2$) program was perfectly efficient. In their study, the potential gains were measured as the difference between a plant's maximal electricity output from a tradable $SO_2$ emission permits program and its observed electricity output under the $SO_2$ emission command and control regime. They identified a potential average increase of 4.27 (or 4.32) percent potential electricity generation if the $SO_2$ emission permits were allowed to be traded spatially (or spatially and temporally) among 87 power plants between 1995 and 2005 in the US. Similarly, Färe et al. (2014) further detected the potential gains (measured by kilowatt-hours output) of 80 US coal-fired electric power plants if the missed trades of $SO_2$ permits came into the existing tradable permit program, and the potential gains if tradable permit systems came into existence for $CO_2$ and $NO_x$ emissions during the period 1995-2005. They compared the production of electricity under command and control emission regulation with that under tradable emission permits regulation, and found an average increase of up to 0.07-2.19 percent in electricity generation if each of these three byproducts had been tradable. In addition, they further identified an even higher average increase in electricity generation (up to 0.74-3.99 percent) if the combinations of these three byproducts, i.e., two of these byproducts or all three of them, had been simultaneously tradable.

Recently, a few studies have tried to analyze the impact of emission permit trading in China. These studies can be divided into two groups. The first focuses on estimating the abatement cost savings from emission permit trading. For example, Zhou et al. (2013) evaluated the economic impact of interregional trading of $CO_2$ emission reduction quotas in China and found that the total emission abatement cost could be reduced by 40 percent through this trading system. Cui et al. (2014) estimated the cost saving effect of $CO_2$ emission permit trading in China based on the 2020 target and identified a total abatement cost reduction of up to 23%. Wang et al. (2015) evaluated the economic impact of emission permit trading among energy intensive sectors (including the electric power industry) in China's Guangdong province and found that it would reduce the abatement cost and make GDP in Guangdong rise by 2.6 billion USD compared to the command and control scenario. The second group of studies pays greater attention to identify the emission reduction effect from emission permit trading. For instance, Liu et al. (2013) simulated the carbon abatement effects of separate emission trading markets and linking markets in Hubei and Guangdong, and pointed out that the linked market would result in higher social welfare and lower $CO_2$ emission intensity than the separated markets. Xu and Masui (2009) analyzed the impacts of local air pollutant emission reduction strategies on climate mitigation and found that an ancillary $CO_2$ reduction benefit could be achieved by introducing $SO_2$ reduction policies in China.

Although these studies provided some good estimations of the impact or cost-saving effect from

$CO_2$ emission permit trading in China, no study, to the best of our knowledge, has as yet provided the estimation of potential gains or unrealized gains achievable and synergy effects from the permit trading of $CO_2$ and other pollutant ($SO_2$ and $NO_x$) emissions specifically for the thermal power industry in China. The current study represents the first attempt to fill this research gap.

We first present three optimization models for efficiency evaluation and unrealized gains estimation, and secondly, three associated schemes for simulating i) a command and control policy instrument and ii) two market-based emission permit trading policy instruments for emission control in China's thermal power industry are proposed based on these three models. Then, we successively calculate the potential increases in electricity generation through i) eliminating technical inefficiency of thermal power industry, ii) allowing spatial trading of $CO_2$ emission permits, and iii) allowing spatial and temporal trading of $CO_2$ emission permits. Finally, we apply these detected potential increases in electricity generation to identify the unrealized gains from eliminating regulatory rigidity of emission permits trading. In other words, these calculations provide estimations of unrealized gains or abatement cost savings from allowing tradable $CO_2$ emission permits among different thermal power industry sectors in China's different provinces and over different periods under estimation so that both the operational inefficiency and the suboptimal allocation of emission permits are eliminated. We conduct this estimation through an ex post analysis for both the pilot emission permits trading markets and a potential unified emission permits trading market in this study.

The remainder of this study is organized as follows. In the next section, the models and schemes for estimating the unrealized gains that can be realized from emission permit trading are proposed. In Section 3, the estimation results for pilot and unified emission permit trading markets are reported and discussed. The synergy effects on the emission abatement process are analyzed in Section 3. The last section concludes the findings of this study.

## 2 Models and schemes

The model for estimating the unrealized gains in this study can be seen as a variation of Brännlund et al. (1998), which seeks to maximize the profit of each entity, and an extension of Färe et al. (2013) and Färe et al. (2014), which seek to maximize the desirable output of each entity. We use desirable output maximization as the objective function instead of profit maximization in order to avoid invoking prices for desirable output and inputs, and we present a more general model that incorporates both weakly disposable and freely disposable undesirable outputs.

The entities under evaluation in this study are provincial thermal power industry sectors, and for each sector, the electricity generation is taken as the desirable output. The byproducts of the thermal power industry are air pollutants such as $SO_2$, $NO_x$ and $CO_2$ emissions. The inputs of the thermal power industry are installed capacity, employees and fuel (coal and oil) consumption.

We denote the provincial thermal power industry sector by DMU$_j$ ($j$=1,…,$n$), inputs by $x_{ij}$ ($i$=1,…,$m$), desirable output by $y_j$, and undesirable outputs by $b_{fj}$ ($f$=1,…,$h$). Following Färe et al. (1989), we first present the environmental production technology set as $P(x)=\{(y,b): x \text{ can produce } (y,b)\}$. In $P(x)$, inputs and desirable outputs are respectively freely disposable, but the undesirable outputs and desirable are jointly weakly disposable[§] and nulljoint. Weak disposability is expressed as if $(y,b)\in P(x)$ and $0\le\theta\le 1$, then $(\theta y,\theta b)\in P(x)$, and nulljointness is expressed as if $(y,b)\in P(x)$ and $b$=0, then $y$=0. Note that the nulljointness can be tested from the data as follows: the conditions $\sum_{j=1}^{n} b_{fj}^t > 0,\ f=1,\dots,h$, and $\sum_{j=f}^{h} b_{fj}^t > 0,\ j=1,\dots,n$, must hold.

To estimate the maximum electricity generation, we utilize the Data Envelopment Analysis model. Firstly, we assume that the command and control regulations on emissions are imposed, which means that there are no tradable permits for undesirable outputs. Then, the maximum electricity generation for each province $l$ ($l$=1,…,$n$) at period $t$ ($t$=1,…,$T$) under the command and control scheme can be estimated as in Model (1).

$$
\begin{aligned}
& R_l^{NTt} = \max \tilde{y}_l^t \\
& s.t.\ \sum_{j=1}^{n} \lambda_j^t y_j^t \ge \tilde{y}_l^t \\
& \qquad \sum_{j=1}^{n} \lambda_j^t b_{fj}^t = b_{fl}^t \qquad f=1,\dots,h \qquad\qquad (1) \\
& \qquad \sum_{j=1}^{n} \lambda_j^t x_{ij}^t \le x_{il}^t \qquad i=1,\dots,m \\
& \qquad \lambda_j^t \ge 0 \qquad\qquad\qquad j=1,\dots,n
\end{aligned}
$$

The desirable outputs and the inputs in Model (1) are freely disposable, while the undesirable outputs are jointly weakly disposable (together with desirable output and denoted by the equation constraint)[**]. In Model (1), $x_{ij}^t$, $x_{il}^t$, $y_j^t$, $b_{fj}^t$, $b_{fl}^t$ are observed inputs, desirable and undesirable

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[§] In the literature applying DEA based methods, the relationship between undesirable and desirable outputs can also be formulated in several different ways: i) Incorporating undesirable outputs in traditional DEA framework through data transformations (e.g., Seiford and Zhu, 2002). However, this approach is not translation invariant. ii) Undesirable outputs are treated as free disposable inputs (Yang and Pollitt, 2009, 2010). However, this treatment is not relevant when the regular inputs (e.g., labor or capital) and pollutions (undesirable outputs treated as inputs) are not substitutes (Adler and Volta, 2016). iii) Eco-efficiency models are utilized instead of traditional DEA models so that only undesirable outputs are utilized as inputs to produce desirable outputs (Mahlberg et al., 2011). However, this method is based on an incomplete production possibility set in that the input factors are ignored (Dakpo et al., 2016). iv) The approach based on materials balance principle that assumes the quantity of a specific material in the inputs must be equal to the amount in outputs including residuals (undesirable outputs) (Coelli et al., 2007; Rødseth et al., 2016). However, this approach ignores the possible interaction existing between those material inputs (e.g., sulfur in fuel consumption) and non-material inputs (e.g., capital investment in $SO_2$ abatement technology). In addition, this approach has the problem of lacking widely accepted weights to commonly measure different material inputs (Dakpo et al., 2016). Thus, the above approaches are not discussed here in this study.

[**] Although the weak disposability assumption has some drawbacks such as violating the first law of

outputs, while $\tilde{y}_l^t$ and $\lambda_j^t$ are desirable output variables and intensity variables that maximization occurs. Thus, $R_l^{NTt}$ denotes the maximum desirable output that thermal power industry sector can obtain in province $l$ at period $t$ when it is only allowed to produce the observed undesirable outputs $b_{fl}^t$. The sum of $R_l^{NTt}$ of all $l$=1,…,$n$ provinces is the maximum total desirable output that the thermal power industry can obtain at each period $t$.

Secondly, for the estimation of maximum electricity generation at each period $t$ when emission permit trading is allowed for some of the undesirable outputs, the maximum total electricity generation for all provinces at period $t$ can be estimated as in Model (2).

$$
\begin{aligned}
& TR_t^{ST} = \max \sum\nolimits_{l=1}^{n} \tilde{y}_l^t \\
& s.t. \ \sum\nolimits_{j=1}^{n} \lambda_{jl}^t y_j^t \ge \tilde{y}_l^t \qquad l = 1,\dots,n \\
& \qquad \sum\nolimits_{j=1}^{n} \lambda_{jl}^t b_{fj}^t = b_{fl}^t \qquad f = 1,\dots,h_1 \quad l = 1,\dots,n \\
& \qquad \sum\nolimits_{j=1}^{n} \lambda_{jl}^t b_{fj}^t = \tilde{b}_{fl}^t \qquad f = h_1+1,\dots,h \quad l = 1,\dots,n \qquad (2) \\
& \qquad \sum\nolimits_{j=1}^{n} \lambda_{jl}^t x_{ij}^t \le x_{il}^t \qquad i = 1,\dots,m \quad l = 1,\dots,n \\
& \qquad \lambda_{jl}^t \ge 0 \quad j = 1,\dots,n \qquad l = 1,\dots,n \\
& \qquad \sum\nolimits_{l=1}^{n} \tilde{b}_{fl}^t \le \sum\nolimits_{l=1}^{n} b_{fl}^t \qquad f = h_1+1,\dots,h
\end{aligned}
$$

In Model (2), the desirable output and the inputs are freely disposable, while we assume the undesirable outputs are all jointly weakly disposable. Similarly, in Model (2), $x_{ij}^t$, $x_{il}^t$, $y_j^t$ are observed inputs and desirable outputs, $b_{fj}^t$, $b_{fl}^t$ are observed undesirable outputs not subject to emission permit trading. $\tilde{y}_l^t$ and $\lambda_j^t$ are desirable output variables and intensity variables that maximization occurs, and $\tilde{b}_{fl}^t$ are also variables indicating undesirable outputs that are tradable. Thus, $\sum\nolimits_{l=1}^{n} b_{fl}^t$, $f$=$h_1$+1,…,$h$, which is the sum of the observed tradable emissions of the thermal

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thermodynamics, we apply this approach in this study because of the following concerns. i) It treats pollution as output (instead of input) and thus does not violate the physical laws and reflects the true production process. ii) It appropriately describes a situation where outputs are tightly linked and cannot be adjusted independently. iii) Under certain conditions, such as there being end-of-pipe technologies for pollution abatement, it is compatible with the materials balance principle. Moreover, such end-of-pipe equipment has becoming increasingly technologically available (e.g., carbon capture, use and storage technologies and demonstrations) and economically affordable (e.g., scrubbers for desulfurization and denitrification in coal-fired power plants). iv) The problems of the existence of strongly dominated projection targets and associated downward-sloped parts of technology can be additionally detected and discarded (Picazo-Tadeo and Prior, 2009) so as to avoid the possible misclassification of efficiency status in weak disposability modelling. In addition, through an appropriate choice of directional vector for projection, these problems also can be avoided. iv) In certain conditions, to treat different undesirable outputs with both weak disposability and free disposability assumptions, as well as with input-treatments can be simultaneously modeled within a generalized DEA framework (Adler and Volta, 2016) so as to meet specific efficiency evaluation demand appropriately.

power industry sectors of all provinces at period *t*, should exceed or at least equal the sum of the optimized tradable emissions $\sum_{l=1}^{n}\tilde{b}_{fl}^{t}$, $f=h_1+1,\ldots,h$, in the same period. $TR_t^{ST}$ denotes the maximum total desirable output that the thermal power industry can obtain in each period *t* when emission permit trading is allowed for undesirable outputs $b_{fl}^{t}$, $f=h_1+1,\ldots,h$.

Thirdly, Model (3) makes it possible to estimate the maximum electricity generation when emission permit trading is allowed not only among provincial thermal power industry sectors but also over different periods.

$$
\begin{aligned}
& TTR^{STT} = \max \sum_{t=1}^{T}\sum_{l=1}^{n}\tilde{y}_l^t \\
& s.t.\ \sum_{j=1}^{n}\lambda_{jl}^t y_j^t \ge \tilde{y}_l^t \\
& \quad \sum_{j=1}^{n}\lambda_{jl}^t b_{fj}^t = b_{fl}^t \quad f=1,\ldots,h_1 \quad l=1,\ldots,n \quad t=1,\ldots,T \\
& \quad \sum_{j=1}^{n}\lambda_{jl}^t b_{fj}^t = \tilde{b}_{fl}^t \quad f=h_1+1,\ldots,h \quad l=1,\ldots,n \quad t=1,\ldots,T \\
& \quad \sum_{j=1}^{n}\lambda_{jl}^t x_{ij}^t \le x_{il}^t \quad i=1,\ldots,m \quad l=1,\ldots,n \quad t=1,\ldots,T \\
& \quad \lambda_{jl}^t \ge 0 \quad j=1,\ldots,n \quad l=1,\ldots,n \quad t=1,\ldots,T \\
& \quad \sum_{t=1}^{T}\sum_{l=1}^{n}\tilde{b}_{fl}^t \le \sum_{t=1}^{T}\sum_{l=1}^{n}b_{fl}^t \quad f=h_1+1,\ldots,h
\end{aligned}
\tag{3}
$$

The freely or weakly disposable assumptions on inputs, desirable and undesirable outputs in Model (3) are the same as those in Model (2), while Model (3) seeks to maximize the total desirable output that the thermal power industry can obtain over the entire study period *t* ($t=1,\ldots,T$). Therefore, the sum of the observed tradable emissions of the thermal power industry sectors of all provinces over the entire study period, $\sum_{t=1}^{T}\sum_{l=1}^{n}b_{fl}^{t}$, $f=h_1+1,\ldots,h$, should exceed or at least equal $\sum_{t=1}^{T}\sum_{l=1}^{n}\tilde{b}_{fl}^{t}$, $f=h_1+1,\ldots,h$, which is the sum of the optimized tradable emissions of all provinces over the entire study period. Similarly, $TTR^{STT}$ denotes the maximum total desirable output that thermal power industry can obtain over the entire study period when emission permit trading is allowed for undesirable outputs $b_{fl}^{t}$, $f=h_1+1,\ldots,h$.

In this study, we have three undesirable outputs ($CO_2$, $SO_2$ and $NO_x$) from the thermal power industry. In many cases, pollutant emissions are tied to fuel consumption. Reducing $CO_2$, $SO_2$ or $NO_x$ emission is usually related to reducing energy consumption and thus leads to reducing electricity production. Therefore, we assume the $CO_2$, $SO_2$ and $NO_x$ emissions to be joint weakly disposable undesirable outputs together with electricity production output.

Before ending this section, we must discuss additional two concerns. First, one may argue that in certain conditions, $SO_2$ and $NO_x$ emissions can be reduced by the installation of scrubbers and thus, in contrast to from $CO_2$ emissions, $SO_2$ and $NO_x$ are indirectly linked with electricity generation or fossil fuel consumption, and should be modeled as freely disposable undesirable outputs. However, this assumption is not in fact appropriate, since the installation and running of scrubbers will lead to transfer some capital input and energy input which were originally used for electricity generation, or directly consume some electricity generated from the power plant, thus leading the reduction in desirable outputs. Second, it should be noted that there is a more recent undesirable output treatment approach that suggests modeling the production process through two separate sub-technologies, of which the first generates desirable outputs and the second generates undesirable outputs. The by-production model proposed by Murty et al. (2012) and the natural and managerial disposability model proposed by Sueyoshi and Goto (2010, 2012) are two representatives of these approaches. The former approach assumes cost disposability of the production and environmental technology regarding undesirable outputs (e.g., $SO_2$ emissions), some desirable output (e.g., electricity generation), and pollution-generating input such as coal (sulfur-containing coal). This approach assumes there is a minimal production of undesirable output that can be by-produced by the technology given some pollution-generating inputs and some desirable outputs fixed at the current levels. The latter approach provides an operational efficiency measure with natural disposability concept, and an environmental efficiency measure with the managerial disposability concept. As suggested by Dakpo et al., (2016) and Førsund (2009), these approaches based on multiple frontier technologies may be promising in future research of undesirable output efficiency evaluation.

We end this section with a summary of the three models and associated schemes. Model (1) provides the no tradable emission permit estimation or the command and control estimation, which calculates the maximum electricity generation of the thermal power industry sector of each province at period $t$. The difference between the maximum electricity generation estimated through Model (1) and the observed electricity generation denotes the effect of eliminating technical inefficiency of the thermal power industry sectors, which can be seen as the unrealized gains caused by technical inefficiency. Model (2) provides the spatial tradable emission permits estimation which calculates the maximum electricity generation of the thermal power industry sectors of all provinces at period $t$ when suboptimal spatial allocation of emission permits is eliminated. Thus, the difference between the estimation of Model (2) and the sum of $n$ estimations of Model (1) denotes the effect of additionally eliminating special regulatory rigidity, which can be seen as the unrealized gains caused by not allowing emission permit trading among different provinces within each period. Model (3) provides the spatial and temporal tradable emission permits estimation, which calculates the maximum electricity generation of the thermal power industry sector of all provinces over the entire study period, when suboptimal spatial and temporal allocation of emission permits is eliminated.

Therefore, the difference between the estimation of Model (3) and the sum of the *T* estimations of Model (2) denotes the effect of additionally eliminating temporal regulatory rigidity (i.e., allowing for depositing and borrowing emission permits), which can be seen as the unrealized gains caused by not allowing emission permit trading over different periods. The unrealized gains estimated in Models (2) and (3) also represent the estimated $CO_2$ and pollutant emissions abatement cost savings in the thermal power industry sector or $CO_2$ and pollutant emissions control leaded electricity generation loss recoveries from implementing interprovincial emission permit trading (Model (2)) and, in addition, intertemporal (Model (3)) emission permit trading policy instruments rather than relying only on a command and control policy (Model (1)) for the thermal power industry.

In the next section, we successively conduct the estimations through Models (1), (2) and (3), in order to detect the unrealized gains gradually through i) eliminating technical inefficiency; ii) additionally eliminating spatial trading rigidity; and iii) additionally eliminating temporal trading rigidity. These three estimations are obtained both from the hypothetical linking of pilot emission permits trading markets and from the potential establishment of unified emission permits trading market in China. Furthermore, Models (1) to (3) are additionally applied for the estimation of unrealized gains of synergy effects in multiple emission abatement process, i.e., supposing trading of $SO_2$ and $NO_x$ of the thermal power industry are additionally allowed among regions and over time in China.

## 3 Estimation results

### 3.1 Data

Our estimation is implemented for the thermal power industry sectors of China's 30 provincial regions during the 11th FYP period, and is an ex post analysis based on the observed historical data. The observed data on emission output and electricity output for 2006-2010 are taken as the baseline for estimating the unrealized gains caused by technical inefficiency, and by not allowing for spatial and temporal emission permit trading.

The regions in the estimation include 4 municipalities as well as 26 provinces and autonomous regions. Tibet, Taiwan, Hong Kong and Macau are not included because of a lack of data and the fact that they are not involved in China's national emission control regulations and policies. Table A1 in Appendix section illustrates these regions, which are further clustered into 8 economic-geographic areas: Northeast (Liaoning, Jilin, Heilongjiang), Northern coast (Beijing, Tianjin, Hebei, Shandong), Eastern coast (Shanghai, Jiangsu, Zhejiang), Southern coast (Fujian, Guangdong, Hainan), Middle reaches of Yellow River (Shanxi, Inner Mongolia, Henan, Shaanxi), Middle reaches of Yangtze River (Anhui, Jiangxi, Hubei, Hunan), Southwest (Guangxi, Chongqing, Sichuan, Guizhou, Yunnan), and

Northwest (Gansu, Qinghai, Ningxia, Xinjiang).

Three inputs of thermal power industry are used in the estimation, for which the data on installed capacity were collected from the China Electricity Yearbook (2007-2011), the data on employees from the China Industry Economy Statistical Yearbook (2007-2011), and the data on fuel consumption (including coal, oil and natural gas consumption) from the energy balance pivot table of each province in China's Provincial Energy Statistical Yearbook (2007-2011) and Electric Power Industry Statistics (2010). Coal, oil and natural gas consumptions are all converted to coal equivalent according to the conversion factors from physical unit to coal equivalent listed in the China Energy Statistical Yearbook (2006). The only desirable output is electricity generation and the data on this were obtained from the China Electricity Yearbook (2007-2011). Three undesirable outputs are used for estimating the unrealized gains if part or all of them are not allowed for emission permit trading. The data on $SO_2$ and $NO_x$ were collected from the Annual Statistical Report on the Environment in China (2007-2010); while the data on $CO_2$ are estimated based on the total fossil fuel consumption and according to the average net calorific value and the default carbon emission factors for fossil fuel combustion respectively provided in the China Energy Statistical Yearbook (2006) and IPCC (2006)[††], as the regional data on $CO_2$ of thermal power industry sector are not available in China's official statistics. Descriptive statistics of the input and output data are presented in Table 1. Note that our data set support the nulljointness conditions.

**[Insert Table 1 here]**

### 3.2 Estimation results and discussions

During our study period (the 11th FYP period), China had not yet established a greenhouse gas emission permit trading market, and China's national and provincial energy consumption intensity reduction and related carbon emission intensity reduction regulations, as well as air pollutant emission reduction regulations were implemented as command and control policy instruments for

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[††] These fossil fuels include raw coal, cleaned coal, washed coal, coke, coke oven gas, coal gas, crude oil, gasoline, kerosene, diesel oil, fuel oil, liquefied petroleum gas, refinery gas, and natural gas. They are firstly converted into calorific values according to the average net calorific values (unit: Joule/Gram) provided by the China National Bureau of Statistics, and then converted into $CO_2$ emissions according to the default emission factors (unit: Gram $CO_2$/Joule) suggested in the IPCC Guidelines for National Greenhouse Gas Inventories (Default emission factors for stationary combustion in the energy industry). The feature on calorific value of specific fossil fuel produced and combusted in China can be characterized and the most commonly accepted emission factors are applied in order to ensure the $CO_2$ estimations are appropriate. In addition, through separately calculating the total fuel consumptions and the total $CO_2$ emissions of China's regional thermal power industry sector, it can be ensured that the data on $CO_2$ emissions are neither tied to total fuel consumption nor proportional to specific energy inputs of coal, oil, or natural gas, which helps to increase the effectiveness of our estimation on unrealized gains. The average net calorific values for different fossil fuels provided in the China Energy Statistical Yearbook (2006-2011) are same. Thus, for unification, we would refer to the data in this study as those in the 2006's yearbook.

emission control. Therefore, the observed pollutant emission and $CO_2$ emission as well as the observed electricity generation from the thermal power industry sectors of China's provincial regions during the study period are taken as the base case (i.e., a command and control scheme with technical inefficiency) for estimating the unrealized gains caused by technical inefficiency (i.e., a command and control scheme), and caused by not allowing for an emission permit spatial trading or spatial and temporal trading scheme. In this case, the observed total levels of $CO_2$, $SO_2$ or $NO_x$ of China's thermal power industry are then respectively considered as the aggregate levels of emission permits.

### 3.2.1 Unrealized gains of pilot emission permits trading markets

Recently, China launched its pilot greenhouse gas emission permit trading markets in seven regions, including four municipalities (Beijing, Tianjin, Shanghai and Chongqing), two provinces (Guangdong and Hubei), and one city (Shenzhen). The establishment of the pilot markets is considered as the first step in establishing China's unified national carbon emission trading system during the period 2016-2020 (NDRC, 2014). In this section, we first estimate the unrealized gains that could be obtained for these pilot regions if their emission permits trading markets were linked; i.e., we estimate the total maximum electricity generation of all these pilot regions if carbon emission permit trading is allowed among these regions and over the study period. Since Shenzhen is a city in Guangdong province, we combine these two markets in our estimation. Tables 2 and 3 report the estimation results.

**[Insert Table 2 and Table 3 here]**

Table 2 reports the annual (second to sixth columns) and 5-year total (last column) results of these six pilot regions of the command and control estimation and the $CO_2$ emission permit spatial trading estimation; while Table 3 reports the similar annual and 5-year total results of the command and control estimation and the $CO_2$ emission permit spatial and temporal treading estimation. The second and third rows of Tables 2 and 3 represent the total value of the observed electricity generation and associated $CO_2$ emission, which are taken as the base case; the fourth and fifth rows of Tables 2 and 3 report the electricity generation and associated percentage increase in electricity generation (compared with the base case) after eliminating technical inefficiency; the sixth and seventh rows report the electricity generation and associated percentage increase when spatial $CO_2$ trading is allowed (Table 2) or spatial and temporal $CO_2$ trading is allowed (Table 3), while the last two rows report the $CO_2$ emission and associated percentage increase after spatial $CO_2$ trading (Table 2) or spatial and temporal $CO_2$ trading is allowed (Table 3).

The estimations in Table 2 reveal a total potential increase of 1.70% in electricity generation during the 11th FYP period for the thermal power industry sectors of China's pilot $CO_2$ trading market regions if technical inefficiency is eliminated. The estimations in Table 2 also indicate that an additional total potential increase in electricity generation of 1.11% can be achieved if intra-period allocation inefficiency of $CO_2$ emission permits is eliminated for these pilot regions. In addition, a total potential decrease in $CO_2$ emission (-0.86%) from the thermal power industry sector of these pilot regions can be identified if spatial suboptimal allocation of $CO_2$ emission permits is eliminated. These potential increases in electricity generation and potential decrease in $CO_2$ emission from eliminating intra-period allocation inefficiency respectively account for 0.45% of China's total thermal electricity generation and 0.12% of total $CO_2$ emissions from the thermal power industry in China during 2006-2010.

Furthermore, Table 3 reveals a total 8.71% potential increase in electricity generation if technical inefficiency is eliminated. This increase is higher than the estimation in Table 2 because the technical efficiency frontiers applied are different. The former takes a single frontier sustained by all observations from the five years in the estimation, while the latter takes five individual frontiers sustained by observations for each year within the study period. Table 3 also reports an additional total 0.17% increase in electricity generation if both intra-period and inter-period allocation inefficiencies of $CO_2$ emission permits are eliminated, i.e., if both spatial and temporal suboptimal allocations of $CO_2$ emission permits are eliminated. In addition, there will be additional $CO_2$ emission reduction potential (-7.06%) after the spatial and temporal $CO_2$ emission permit trading. The identified potential increase in electricity generation from simultaneously eliminating intra-period and inter-period allocation inefficiencies accounts for 1.42% of China's total thermal electricity generation during the period 2006-2010.

### 3.2.2 Unrealized gains from a unified emission permits trading market

In this section, we estimate the unrealized gains than could be obtained for all 30 of China's regions if a unified $CO_2$ emission permit trading market is established and the thermal power industry sector for each of China's 30 regions is allowed to trade its $CO_2$ emission permits with other regions and over the entire study period (2006-2010). The estimation results are reported in Tables 4 and 5 as well as Tables A1 and A2. These results are aggregated and reported in sum values for each year and for all five years across the thermal power industry sectors (Tables 4 and 5), and reported in sum values for each thermal power industry sector across years (Tables A1 and A2).

**[Insert Table 4 and Table 5 here]**

Table 4 reports the spatial trading estimation. The fourth row of Table 4 shows that there is a total

2.04% increase potential in electricity generation during the 11th FYP period for the thermal power industry sectors of China's 30 regions if technical inefficiency is eliminated, and the percentages of potential increases range from 1.54% (in 2006) to 2.62% (in 2010). Then, the sixth row shows that if intra-period allocation inefficiency of $CO_2$ emission permits is eliminated for the thermal power industry sectors of China's 30 regions, there is an additional 1.50% total increase potential in electricity generation during 2006-2010, which is associated with a total 0.73% decrease potential in $CO_2$ emissions from China's thermal power industry during the same period. The total thermal electricity generation of China during 11th FYP period is 14306.25 billion kWh, and the unrealized gains that can be obtained through eliminating special regulatory rigidity (i.e., eliminating intra-period $CO_2$ emission permits allocation inefficiency) account for 3.71% of China's total thermal electricity generation.

The spatial trading estimation results of China's 30 provincial regions and 8 economic-geographic areas are additionally reported in Table A1 in Appendix section. The results in Table A1 further indicate that the Southwest area benefits most from spatial $CO_2$ emission permit trading as it achieves the highest percent increase in electricity generation (2.85%). The percentages of potential electricity increases of the other 7 areas are all higher than 0.65% and range from 0.67% (Northeast area) to 2.32% (Northwest area). The percentage increase in $CO_2$ emissions with spatial $CO_2$ trading shown in Table A1 offers the information on the pattern of spatial $CO_2$ emission permit trading. Regarding the entire study period, the Eastern coast, Southern coast, Middle reaches of Yangtze River and Northwest areas are the buyers of the permits, while the Northeast, Northern coast, Middle reaches of Yellow River and Southwest areas are the sellers of the permits if the permits are allowed to be spatially traded among China's 30 regions.

Table 5 reports the spatial and temporal trading estimation. The potential increase in electricity generation from eliminating technical inefficiency (shown in the fourth row) is identified as a total of 6.76% for the entire study period, and the potential increases range from 5.31% (in 2010) to 8.01% (in 2006), all of which are higher than their counterparts in Table 4. The explanations are same as for the analysis in Section 3.2.1. The 5-year global frontier which is used for spatial and temporal trading estimation incorporates each year's individual frontiers which are used only for spatial trading estimation, and the distance between observation and global frontier is not less than that between observation and the single year's individual frontier. Then, if the intra-period and inter-period allocation inefficiency of $CO_2$ emission permits is eliminated, there is an additional 1.62% total potential increase in electricity generation from China's thermal power industry over the entire study period (shown in the sixth row), and these potential increases from spatial and temporal trading range from 0.68% (in 2010) to 2.38% (in 2008). The associated changes in $CO_2$ emissions range from -5.75% (in 2009) to 0.50% (in 2006), and show a potential decrease of 3.43% in total $CO_2$ emissions from China's thermal power industry over the entire study period. Similar to the calculation above for the spatial trading estimation, during the 11th FYP period, the unrealized gains that can be obtained from simultaneously eliminating special and temporal regulatory rigidity (i.e., simultaneously eliminating allocation inefficiency of intra-period and inter-period $CO_2$ emission permit) account for 8.63% of China's total thermal electricity generation.

The spatial and temporal trading estimation results of China's 30 provincial regions and 8 economic-geographic areas are reported in Table A2 in Appendix section. It can be seen that the Southwest area has the highest percent increase in electricity generation (4.98%) followed by the Middle reaches of Yellow River area (2.70%) and the Eastern coast area (1.21%). In addition, all the remaining areas can benefit from spatial and temporal $CO_2$ emission permit trading as their potential electricity increase percentages are all higher than 0.5 percent. However, the pattern of spatial and temporal $CO_2$ emission permit trading shown in Table 5 is a little different from that in Table 4. Eastern coast, Southern coast and Northwest areas have positive percentages, indicating that these three areas the main buyers of the $CO_2$ emission permits when they are allowed to be traded among China's 30 regions and over the entire study period. The remaining five areas are shown to be the sellers of $CO_2$ emission permits. In this case, that there are fewer buyers than sellers indicating that buyers are buying from several sellers.

In the spatial trading estimation, there are 15 sellers (i.e., provinces) and 15 buyers of $CO_2$ emission permits, while in the spatial and temporal trading estimation, the situation changes to 20 sellers and 10 buyers. Most of the buyers are located in China's economically well-developed east and south coast areas, as well as the northwest and southwest areas which have comparatively abundant energy deposits such as coal, oil and hydro power, while most of the sellers are regions in China's northern cost and northeast areas which import large amount of thermal electricity from neighboring regions and have experienced comparatively noticeable transformation and upgrading in their industries. Figure 1 illustrates the approximate estimated fluxes of $CO_2$ emission permits in spatial and temporal trading of the thermal power industry in China.

**[Insert Figure 1 here]**

### 3.2.3 Unrealized gains of synergy effects in multiple emission abatement process

In this section, we also take another two undesirable outputs ($SO_2$ and $NO_x$) of the thermal power industry into estimation, supposing that they are also allowed to be traded among China's 30 regions and over time. When simultaneously modeling two ($CO_2$ and $SO_2$) or three ($CO_2$, $SO_2$ and $NO_x$) undesirable outputs, the effects of the synergies in multiple emission abatement processes, which are represented by the additional unrealized gains achievable through multiple emission permit trading, can be estimated. The results allow us to identify the net effect of a multiple emission permit trading scheme on the electricity generation of each thermal power industry sector. The estimation results are reported in sum values for each year across the thermal power industry sectors and can be found in Table A3 in Appendix section.

The second column reports the observed electricity generation of each thermal power industry sector in the base case, and the third column reports the electricity generation after eliminating technical inefficiency. Here, the 5-year global frontier is used for the inefficiency measurement; thus the results are the same as those in Table A2. The fourth column reports the electricity generation when only $CO_2$ emission permits are allowed to be traded spatially and temporally; i.e., the electricity generation when both spatial and temporal regulatory rigidities are simultaneously eliminated for a single undesirable output ($CO_2$).

The fifth and sixth columns provide the estimations and associated percentage changes when combinations of two undesirable outputs ($CO_2$ plus $SO_2$) are allowed to be spatially and temporally traded simultaneously. 26 regions are found to have higher electricity generation when $SO_2$ emission permits are additionally allowed to be traded (associated with $CO_2$ emission permit trading) compared to when only $CO_2$ emission permits are allowed to be traded. This estimation indicates a positive synergy effect in the multiple emission abatement process of $CO_2$ and $SO_2$. The remaining 4 regions show lower or equal electricity generation from combined $CO_2$ and $SO_2$ emission permit trading, which indicates a negative or zero synergy effect. For the entire thermal power industry in China, this net synergy effect of the multiple emission abatement process of $CO_2$ and $SO_2$ is positive since the percentage increase in electricity generation with spatial and temporal $CO_2$ and $SO_2$ emission permit trading (compared with that of only $CO_2$ emission permit trading) is 0.94%. In addition, the results also reveal that the Southwest area exhibits the largest positive synergy effect, as its electricity generation increases by 3.04% when $CO_2$ and $SO_2$ emission permits are tradable simultaneously; while the Middle reaches of Yangtze River area exhibits the lowest synergy effect that its electricity generation increases by 0.31%.

The seventh and eighth columns provide the estimations and associated percentage changes when combinations of three undesirable outputs ($CO_2$, $SO_2$ plus $NO_x$) are allowed to be spatially and temporally traded simultaneously. In this case, all 30 regions exhibit higher electricity generations when these three undesirable outputs emission permits are allowed to be traded compared with when only $CO_2$ and $SO_2$ emission permits are allowed to be traded. In other words, all Chinese regions exhibit positive synergy effects in the multiple emission abatement process of $CO_2$, $SO_2$ and $NO_x$. For the entire thermal power industry in China, the multiple emission abatement process of $CO_2$, $SO_2$

and $NO_x$ exhibits positive net synergy effect, and the percentage increase in electricity generation with spatial and temporal trading of all three emission permits (compared with that of $CO_2$ and $SO_2$ emission permit trading) is 1.43%. The Southwest area shows the largest positive synergy effect from the trading of three emission permits, while the Northern coast area shows the lowest synergy effect. The electricity generation of the former increases by 2.74%, while that of the latter increases by 0.90% when $CO_2$, $SO_2$ and $NO_x$ emission permits are simultaneously tradable.

The above estimations reveal that in general, electricity generation from the thermal power industry in China increases further when two ($CO_2$ and $SO_2$) or three ($CO_2$, $SO_2$ and $NO_x$) emissions are simultaneously tradable than when only $CO_2$ emissions are tradable. This result indicates the existence of a positive net synergy effect in the emission abatement process of China's thermal power industry. Furthermore, the estimations show that the additional unrealized gains that can be obtained through multiple emission permit trading of two emissions or three emissions account for 1.02% or 2.58% respectively of China's total thermal electricity generation during the 11th FYP period.

## 4 Conclusions

The dominance of thermal power in China's electricity generation and the dominance of coal consumption in China’s thermal power sector make this sector one of the most influential agents in determining China’s overall $CO_2$ emission level, as well as other air pollutants. Emission permit trading is known as an efficient market-based policy instrument for achieving the joint target of economic growth and emission reduction, and expected to surpass command and control policy instruments in term of emission mitigation efficiency. This is particularly true if abatement cost varies across emission agents. This study offers an evaluation of the efficiency advantage of permit trading system. We estimate the potential gains achievable for the thermal power industry in China if constraints on inter-period and inter-region trading were all eliminated. The potential gains are evaluated with the potential increase in thermal electricity generation.

According to our estimation, i) the electricity generation of China's pilot greenhouse gas emission trading market regions would increase by 2.83% or 8.89%, respectively, if technical inefficiency was eliminated and $CO_2$ emission permits were allowed to be spatially or spatial-temporally traded among these pilot markets; ii) including the elimination of technical efficiency, if the intra-period allocation inefficiency of $CO_2$ emission permits was eliminated through spatial trading for the thermal power industry sectors of China's 30 regions, there would be a potential 3.57% total increase potential in electricity generation, while if both the intra-period and inter-period allocation inefficiency of $CO_2$ emission permits was eliminated though spatial and temporal trading for the thermal power industry sectors of China's 30 regions, there would be a potential 8.48% total increase in electricity generation.

The supply of and the demand for $CO_2$ emission permits are also identified in our work. Regions located in the areas of Northeast, Northern coast, Middle reaches of Yellow River, Middle reaches of Yangtze River, and Southwest areas would be sellers of $CO_2$ permits in China, while those located in Eastern coast area, Southern coast area, and Northwest area would be the buyers of $CO_2$ emission permits, if the permits were both spatially and temporally tradable.

We further analyze the scenario in which combinations of two ($CO_2$ plus $SO_2$) or three ($CO_2$, $SO_2$ plus $NO_x$) greenhouse gases are traded in an integrated market. This would result in an additional increase of 0.94% or 1.43% electricity generation in China's thermal power industry, which indicates positive net synergy effects from a multiple emission abatement process.

The extent to which we can benefit from market based policy instruments depends on the heterogeneity of abatement costs among thermal power plants. Introduction of a carbon emission permits trading scheme in China’s thermal power industry would offer power plants with high marginal carbon abatement costs an opportunity to purchase an allowance of $CO_2$ emissions from those with relatively low abatement costs. Therefore, emission permits trading will yield abatement cost savings for society as a whole. At the current stage, China is under great pressure to maintain its economic growth while controlling carbon emissions. Although the Chinese government is paying increasing attention to diverting electricity generation to renewable energy, China’s dependence on coal-based electricity production will not change, at least in the next 15 to 20 years, considering its resources endowment. Therefore, emission permits trading should be considered as an important policy alternative and given priority in China’s future emission reduction policy making. The potential gains identified in this study help to clarify the savings in emission abatement costs from emission permit trading, and therefore provide good arguments for establishing a nationwide emission permit trading system in the near future.

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## Appendix

**[Insert Tables A1, A2 and A3 here]**

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## Figures and Tables

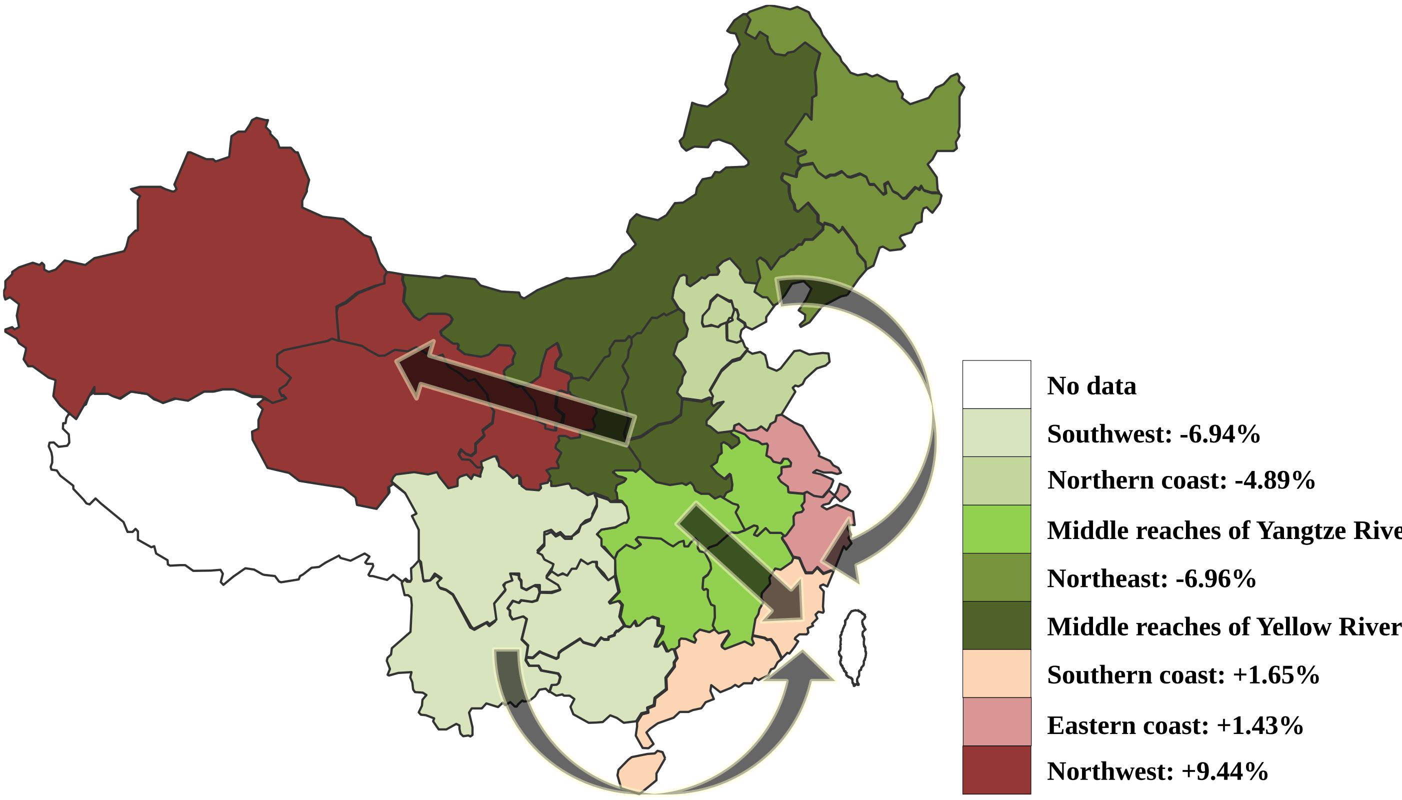

**Figure 1 China's 8 economic-geographic areas and estimated fluxes of $CO_2$ emission permits in spatial and temporal trading**

Table 1 Descriptive statistics for the input and output data (30×5 observations)

| | | 2006 | 2007 | 2008 | 2009 | 2010 |
|---|---|---|---|---|---|---|
| **$x_1$** | Mean | 16.13 | 18.48 | 20.09 | 21.70 | 23.65 |
| **Installed capacity** | Std. Dev. | 13.86 | 15.12 | 15.64 | 16.28 | 17.44 |
| **Million kw** | Minimum | 1.52 | 1.90 | 2.00 | 1.93 | 1.93 |
| | Maximum | 51.78 | 54.14 | 55.93 | 58.86 | 60.02 |
| **$x_2$** | Mean | 86.21 | 85.52 | 86.34 | 92.42 | 91.76 |
| **Employees** | Std. Dev. | 50.50 | 50.29 | 48.10 | 55.97 | 55.37 |
| **Thousand** | Minimum | 14.30 | 14.40 | 11.80 | 11.80 | 12.10 |
| | Maximum | 206.20 | 193.50 | 201.10 | 232.40 | 220.10 |
| **$x_3$** | Mean | 38.52 | 41.65 | 45.71 | 48.34 | 55.43 |
| **Coal consumption** | Std. Dev. | 31.47 | 32.63 | 36.35 | 37.96 | 42.71 |
| **Million tonnes** | Minimum | 2.59 | 3.10 | 3.25 | 3.35 | 4.27 |
| | Maximum | 123.33 | 118.35 | 123.83 | 128.55 | 152.01 |
| **$x_4$** | Mean | 200.12 | 208.17 | 219.83 | 179.57 | 145.33 |
| **Oil consumption** | Std. Dev. | 730.07 | 830.68 | 934.91 | 812.30 | 689.25 |
| **Thousand tonnes** | Minimum | 0.80 | 2.00 | 1.00 | 1.00 | 0.40 |
| | Maximum | 3985.00 | 4571.00 | 5157.00 | 4474.00 | 3791.00 |
| **$y$** | Mean | 78.99 | 90.76 | 92.86 | 100.38 | 113.88 |
| **Electricity generation** | Std. Dev. | 65.29 | 73.80 | 75.70 | 79.20 | 88.93 |
| **Billion kwh** | Minimum | 7.20 | 9.99 | 9.47 | 10.70 | 10.90 |
| | Maximum | 251.26 | 269.14 | 274.07 | 285.80 | 330.50 |
| **$b_1$** | Mean | 394.79 | 366.31 | 335.19 | 292.42 | 278.24 |
| **$SO_2$ emission** | Std. Dev. | 264.29 | 244.36 | 220.54 | 194.08 | 197.84 |
| **Thousand tonnes** | Minimum | 15.51 | 16.12 | 13.42 | 11.63 | 9.35 |
| | Maximum | 977.49 | 906.57 | 798.51 | 711.59 | 702.32 |
| **$b_2$** | Mean | 218.55 | 238.06 | 235.75 | 244.85 | 284.22 |
| **$NO_x$ emission** | Std. Dev. | 200.88 | 205.84 | 192.73 | 193.01 | 207.58 |
| **Thousand tonnes** | Minimum | 10.09 | 12.21 | 10.97 | 11.23 | 15.22 |
| | Maximum | 782.01 | 798.47 | 666.93 | 663.76 | 818.99 |
| **$b_3$** | Mean | 82.48 | 92.15 | 94.44 | 98.42 | 104.32 |
| **$CO_2$ emission** | Std. Dev. | 63.45 | 69.75 | 73.86 | 75.48 | 79.02 |
| **Million tonnes** | Minimum | 6.77 | 6.87 | 7.18 | 7.80 | 10.12 |
| | Maximum | 240.76 | 250.73 | 259.68 | 273.07 | 277.58 |

**Table 2 Estimation results of spatial trading of $CO_2$ emission permits (total for 6 pilot regions)**

| Year | 2006 | 2007 | 2008 | 2009 | 2010 | Total |
|---|---|---|---|---|---|---|
| **Observed electricity generation (base case)$^*$** | 397.90 | 440.20 | 438.00 | 451.50 | 539.80 | 2267.40 |
| **Electricity generation after eliminating technical inefficiency$^*$** | 401.51 | 444.06 | 445.39 | 456.38 | 558.64 | 2305.98 |
| **Electricity increase % with no technical inefficiency** | 0.91% | 0.88% | 1.69% | 1.08% | 3.49% | 1.70% |
| **Electricity generation with spatial $CO_2$ trading$^*$** | 407.81 | 448.48 | 450.17 | 465.97 | 559.18 | 2331.62 |
| **Electricity increase % with spatial $CO_2$ trading** | 1.57% | 1.00% | 1.07% | 2.10% | 0.10% | 1.11% |
| **Electricity increase % with no inefficiency and with spatial $CO_2$ trading** | 2.49% | 1.88% | 2.78% | 3.21% | 3.59% | 2.83% |
| **Observed $CO_2$ emission (base case)$^\#$** | 393.44 | 420.82 | 402.34 | 403.98 | 444.84 | 2065.42 |
| **$CO_2$ emission with spatial $CO_2$ trading$^\#$** | 393.44 | 415.94 | 402.34 | 403.98 | 432.04 | 2047.74 |
| **$CO_2$ emission increase % with spatial $CO_2$ trading** | 0.00% | -1.16% | 0.00% | 0.00% | -2.88% | -0.86% |

Note: $^*$ in billion kWh, $^\#$ in million tonnes of $CO_2$

**Table 3 Estimation results of spatial and temporal trading of $CO_2$ emission permits (total for 6 pilot regions)**

| Year | 2006 | 2007 | 2008 | 2009 | 2010 | Total |
|---|---|---|---|---|---|---|
| **Observed electricity generation (base case)$^*$** | 397.90 | 440.20 | 438.00 | 451.50 | 539.80 | 2267.40 |
| **Electricity generation after eliminating technical inefficiency$^*$** | 443.64 | 468.14 | 486.09 | 502.00 | 565.04 | 2464.90 |
| **Electricity increase % with no technical inefficiency** | 11.49% | 6.35% | 10.98% | 11.19% | 4.67% | 8.71% |
| **Electricity generation with spatial and temporal $CO_2$ trading$^*$** | 444.35 | 471.57 | 486.09 | 502.00 | 565.04 | 2469.04 |
| **Electricity increase % with spatial and temporal $CO_2$ trading** | 0.16% | 0.73% | 0.00% | 0.00% | 0.00% | 0.17% |
| **Electricity increase % with no inefficiency and with spatial and temporal $CO_2$ trading** | 11.67% | 7.13% | 10.98% | 11.19% | 4.67% | 8.89% |
| **Observed $CO_2$ emission (base case)$^\#$** | 393.44 | 420.82 | 402.34 | 403.98 | 444.84 | 2065.42 |
| **$CO_2$ emission with spatial and temporal $CO_2$ trading$^\#$** | 357.16 | 379.93 | 371.23 | 370.26 | 441.11 | 1919.70 |
| **$CO_2$ emission increase % with spatial and temporal $CO_2$ trading** | -9.22% | -9.72% | -7.73% | -8.35% | -0.84% | -7.06% |

Note: $^*$ in billion kWh, $^\#$ in million tonnes of $CO_2$

**Table 4 Estimation results of spatial trading of $CO_2$ emission permits (total for China's 30 regions)**

| Year | 2006 | 2007 | 2008 | 2009 | 2010 | Total |
|---|---|---|---|---|---|---|
| **Observed electricity generation (base case)$^*$** | 2374.10 | 2720.90 | 2802.80 | 3011.50 | 3416.50 | 14325.80 |
| **Electricity generation after eliminating technical inefficiency$^*$** | 2410.61 | 2782.91 | 2846.95 | 3071.98 | 3506.14 | 14618.58 |
| **Electricity increase % with no technical inefficiency** | 1.54% | 2.28% | 1.58% | 2.01% | 2.62% | 2.04% |
| **Electricity generation with spatial $CO_2$ trading$^*$** | 2455.01 | 2820.01 | 2904.36 | 3113.08 | 3545.16 | 14837.61 |
| **Electricity increase % with spatial $CO_2$ trading** | 1.84% | 1.33% | 2.02% | 1.34% | 1.11% | 1.50% |
| **Electricity increase % with no inefficiency and with spatial $CO_2$ trading** | 3.41% | 3.64% | 3.62% | 3.37% | 3.77% | 3.57% |
| **Observed $CO_2$ emission (base case)$^\#$** | 2474.45 | 2764.58 | 2833.06 | 2952.60 | 3129.57 | 14154.26 |
| **$CO_2$ emission with spatial $CO_2$ trading$^\#$** | 2474.45 | 2764.58 | 2833.06 | 2952.60 | 3026.61 | 14051.30 |
| **$CO_2$ emission increase % with spatial $CO_2$ trading** | 0.00% | 0.00% | 0.00% | 0.00% | -3.29% | -0.73% |

Note: $^*$ in billion kWh, $^\#$ in million tonnes of $CO_2$

**Table 5 Estimation results of spatial and temporal trading of $CO_2$ emission permits (total for China's 30 regions)**

| Year | 2006 | 2007 | 2008 | 2009 | 2010 | Total |
|---|---|---|---|---|---|---|
| **Observed electricity generation (base case)$^*$** | 2374.10 | 2720.90 | 2802.80 | 3011.50 | 3416.50 | 14325.80 |
| **Electricity generation after eliminating technical inefficiency$^*$** | 2564.36 | 2907.16 | 2979.00 | 3245.03 | 3598.07 | 15293.61 |
| **Electricity increase % with no technical inefficiency** | 8.01% | 6.85% | 6.29% | 7.75% | 5.31% | 6.76% |
| **Electricity generation with spatial and temporal $CO_2$ trading$^*$** | 2616.71 | 2960.03 | 3049.79 | 3291.63 | 3622.59 | 15540.75 |
| **Electricity increase % with spatial and temporal $CO_2$ trading** | 2.04% | 1.82% | 2.38% | 1.44% | 0.68% | 1.62% |
| **Electricity increase % with no inefficiency and with spatial and temporal $CO_2$ trading** | 10.22% | 8.79% | 8.81% | 9.30% | 6.03% | 8.48% |
| **Observed $CO_2$ emission (base case)$^\#$** | 2474.45 | 2764.58 | 2833.06 | 2952.60 | 3129.57 | 14154.26 |
| **$CO_2$ emission with spatial and temporal $CO_2$ trading$^\#$** | 2486.91 | 2683.95 | 2691.12 | 2782.94 | 3023.40 | 13668.32 |
| **$CO_2$ emission increase % with spatial and temporal $CO_2$ trading** | 0.50% | -2.92% | -5.01% | -5.75% | -3.39% | -3.43% |

Note: $^*$ in billion kWh, $^\#$ in million tonnes of $CO_2$

**Table A1 Estimation results of spatial trading of $CO_2$ emission permits (2006-2010 total)**

| Regions | Observed electricity generation in base case* | Observed $CO_2$ emission in base case# | Electricity generation after eliminating technical inefficiency* | Percentage increase in electricity with no technical inefficiency | Electricity generation with spatial $CO_2$ trading* | Percentage increase in electricity with spatial $CO_2$ trading | $CO_2$ emission with spatial $CO_2$ trading# | Percentage increase in $CO_2$ emission with spatial $CO_2$ trading |
|---|---|---|---|---|---|---|---|---|
| **Beijing** | 117.60 | 90.80 | 117.60 | 0.00% | 117.60 | 0.00% | 90.80 | 0.00% |
| **Tianjin** | 212.80 | 196.55 | 212.80 | 0.00% | 212.59 | -0.10% | 193.30 | -1.66% |
| **Hebei** | 839.50 | 877.87 | 848.05 | 1.02% | 869.11 | 2.48% | 808.01 | -7.96% |
| **Shanxi** | 895.70 | 851.13 | 895.70 | 0.00% | 902.74 | 0.79% | 874.73 | 2.77% |
| **Inner Mongolia** | 974.80 | 1173.65 | 974.80 | 0.00% | 1017.86 | 4.42% | 1078.18 | -8.13% |
| **Liaoning** | 548.30 | 598.11 | 566.49 | 3.32% | 569.18 | 0.47% | 573.87 | -4.05% |
| **Jilin** | 229.70 | 302.95 | 229.70 | 0.00% | 229.99 | 0.13% | 293.10 | -3.25% |
| **Heilongjiang** | 345.90 | 382.44 | 396.14 | 14.52% | 401.17 | 1.27% | 368.24 | -3.71% |
| **Shanghai** | 395.50 | 390.04 | 395.50 | 0.00% | 395.50 | 0.00% | 390.04 | 0.00% |
| **Jiangsu** | 1408.70 | 1213.18 | 1408.70 | 0.00% | 1408.70 | 0.00% | 1213.18 | 0.00% |
| **Zhejiang** | 881.10 | 742.65 | 885.53 | 0.50% | 920.90 | 3.99% | 799.25 | 7.62% |
| **Anhui** | 536.80 | 487.80 | 545.38 | 1.60% | 547.52 | 0.39% | 496.84 | 1.85% |
| **Fujian** | 380.40 | 319.07 | 380.40 | 0.00% | 380.83 | 0.11% | 315.48 | -1.12% |
| **Jiangxi** | 215.50 | 231.94 | 238.64 | 10.74% | 244.91 | 2.63% | 231.99 | 0.02% |
| **Shandong** | 1347.10 | 1286.44 | 1394.92 | 3.55% | 1399.63 | 0.34% | 1269.37 | -1.33% |
| **Henan** | 934.80 | 958.50 | 979.21 | 4.75% | 979.65 | 0.04% | 953.58 | -0.51% |
| **Hubei** | 312.50 | 315.09 | 313.23 | 0.23% | 313.48 | 0.08% | 316.03 | 0.30% |
| **Hunan** | 291.00 | 282.31 | 320.22 | 10.04% | 329.43 | 2.88% | 298.91 | 5.88% |
| **Guangdong** | 1084.50 | 923.13 | 1112.26 | 2.56% | 1155.97 | 3.93% | 1025.52 | 11.09% |
| **Guangxi** | 196.80 | 191.84 | 196.80 | 0.00% | 196.80 | 0.00% | 191.84 | 0.00% |
| **Hainan** | 54.60 | 39.62 | 54.60 | 0.00% | 54.60 | 0.00% | 39.62 | 0.00% |
| **Chongqing** | 144.50 | 149.79 | 144.50 | 0.00% | 144.50 | 0.00% | 149.79 | 0.00% |
| **Sichuan** | 236.10 | 302.48 | 236.10 | 0.00% | 245.45 | 3.96% | 292.63 | -3.26% |
| **Guizhou** | 437.50 | 441.18 | 437.50 | 0.00% | 437.50 | 0.00% | 441.18 | 0.00% |
| **Yunnan** | 239.10 | 329.25 | 239.10 | 0.00% | 250.15 | 4.62% | 228.92 | -30.47% |
| **Shaanxi** | 357.20 | 377.75 | 357.20 | 0.00% | 357.20 | 0.00% | 377.75 | 0.00% |
| **Gansu** | 228.10 | 211.99 | 245.92 | 7.81% | 250.37 | 1.81% | 215.31 | 1.57% |
| **Qinghai** | 49.30 | 47.57 | 51.19 | 3.83% | 52.59 | 2.74% | 51.32 | 7.89% |
| **Ningxia** | 226.80 | 233.33 | 226.80 | 0.00% | 226.80 | 0.00% | 233.33 | 0.00% |
| **Xinjiang** | 203.60 | 205.79 | 213.62 | 4.92% | 224.88 | 5.27% | 239.16 | 16.22% |
| **Northeast** | 1123.90 | 1283.50 | 1192.32 | 6.09% | 1200.34 | 0.67% | 1235.2 | -3.76% |

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|---|---|---|---|---|---|---|---|---|
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| **Northern coast** | 2517.00 | 2451.67 | 2573.36 | 2.24% | 2598.93 | 0.99% | 2361.48 | -3.68% |
| **Eastern coast** | 2685.30 | 2345.87 | 2689.73 | 0.17% | 2725.10 | 1.31% | 2402.47 | 2.41% |
| **Southern coast** | 1519.50 | 1281.82 | 1547.26 | 1.83% | 1591.40 | 2.85% | 1380.63 | 7.71% |
| **Middle reaches of Yellow River** | 3162.50 | 3361.03 | 3206.91 | 1.40% | 3257.45 | 1.58% | 3284.24 | -2.28% |
| **Middle reaches of Yangtze River** | 1355.80 | 1317.14 | 1417.46 | 4.55% | 1435.35 | 1.26% | 1343.77 | 2.02% |
| **Southwest** | 1254.00 | 1414.54 | 1254.00 | 0.00% | 1274.40 | 1.63% | 1304.37 | -7.79% |
| **Northwest** | 707.80 | 698.68 | 737.53 | 4.20% | 754.64 | 2.32% | 739.13 | 5.79% |
| **China** | 14325.80 | 14154.26 | 14618.58 | 2.04% | 14837.61 | 1.50% | 14051.30 | -0.73% |

Note: * in billion kWh, # in million tonnes of $CO_2$

**Table A2 Estimation results of spatial and temporal trading of $CO_2$ emission permits (2006-2010 total)**

| Regions | Observed electricity generation in base case* | Observed $CO_2$ emission in base case# | Electricity generation after eliminating technical inefficiency* | Percentage increase in electricity with no technical inefficiency | Electricity generation with spatial and temporal $CO_2$ trading* | Percentage increase in electricity with spatial and temporal $CO_2$ trading | $CO_2$ emission with spatial and temporal $CO_2$ trading# | Percentage increase in $CO_2$ emission with spatial and temporal $CO_2$ trading |
|---|---|---|---|---|---|---|---|---|
| **Beijing** | 117.6 | 90.8 | 118.9 | 1.15% | 119.1 | 0.11% | 88.3 | -2.81% |
| **Tianjin** | 212.8 | 196.6 | 212.8 | 0.00% | 214.4 | 0.75% | 190.9 | -2.90% |
| **Hebei** | 839.5 | 877.9 | 872.4 | 3.92% | 883.0 | 1.20% | 802.0 | -8.64% |
| **Shanxi** | 895.7 | 851.1 | 934.2 | 4.29% | 940.3 | 0.66% | 803.6 | -5.58% |
| **Inner Mongolia** | 974.8 | 1173.7 | 1017.4 | 4.37% | 1097.3 | 7.86% | 936.7 | -20.19% |
| **Liaoning** | 548.3 | 598.1 | 585.9 | 6.85% | 588.2 | 0.40% | 556.6 | -6.94% |
| **Jilin** | 229.7 | 303.0 | 229.7 | 0.00% | 234.3 | 2.02% | 279.1 | -7.88% |
| **Heilongjiang** | 345.9 | 382.4 | 416.3 | 20.36% | 418.5 | 0.53% | 358.5 | -6.27% |
| **Shanghai** | 395.5 | 390.0 | 395.5 | 0.00% | 395.5 | 0.00% | 390.0 | 0.00% |
| **Jiangsu** | 1408.7 | 1213.2 | 1455.4 | 3.32% | 1460.1 | 0.33% | 1196.1 | -1.41% |
| **Zhejiang** | 881.1 | 742.7 | 968.3 | 9.90% | 997.6 | 3.02% | 793.3 | 6.82% |
| **Anhui** | 536.8 | 487.8 | 572.4 | 6.62% | 573.3 | 0.16% | 461.0 | -5.49% |
| **Fujian** | 380.4 | 319.1 | 382.2 | 0.46% | 386.8 | 1.20% | 301.8 | -5.40% |
| **Jiangxi** | 215.5 | 231.9 | 250.8 | 16.40% | 252.7 | 0.73% | 224.0 | -3.42% |
| **Shandong** | 1347.1 | 1286.4 | 1467.5 | 8.93% | 1469.7 | 0.15% | 1250.7 | -2.78% |
| **Henan** | 934.8 | 958.5 | 1040.3 | 11.29% | 1042.5 | 0.21% | 985.0 | 2.77% |
| **Hubei** | 312.5 | 315.1 | 331.4 | 6.05% | 336.1 | 1.43% | 284.3 | -9.79% |
| **Hunan** | 291.0 | 282.3 | 349.3 | 20.03% | 352.3 | 0.85% | 289.4 | 2.50% |
| **Guangdong** | 1084.5 | 923.1 | 1205.3 | 11.14% | 1214.5 | 0.77% | 959.0 | 3.89% |
| **Guangxi** | 196.8 | 191.8 | 196.8 | 0.00% | 196.8 | 0.00% | 191.8 | 0.00% |
| **Hainan** | 54.6 | 39.6 | 55.6 | 1.80% | 57.1 | 2.73% | 42.1 | 6.27% |
| **Chongqing** | 144.5 | 149.8 | 157.6 | 9.09% | 168.5 | 6.87% | 170.1 | 13.58% |
| **Sichuan** | 236.1 | 302.5 | 243.8 | 3.28% | 266.6 | 9.33% | 281.4 | -6.98% |
| **Guizhou** | 437.5 | 441.2 | 443.5 | 1.37% | 445.9 | 0.54% | 437.7 | -0.80% |
| **Yunnan** | 239.1 | 329.2 | 241.0 | 0.79% | 268.9 | 11.58% | 235.4 | -28.51% |
| **Shaanxi** | 357.2 | 377.7 | 379.1 | 6.14% | 381.7 | 0.67% | 395.0 | 4.56% |
| **Gansu** | 228.1 | 212.0 | 254.6 | 11.64% | 256.4 | 0.68% | 215.8 | 1.78% |
| **Qinghai** | 49.3 | 47.6 | 52.9 | 7.28% | 54.0 | 2.13% | 59.2 | 24.39% |
| **Ningxia** | 226.8 | 233.3 | 226.8 | 0.00% | 226.8 | 0.01% | 228.2 | -2.21% |
| **Xinjiang** | 203.6 | 205.8 | 235.8 | 15.82% | 241.8 | 2.55% | 261.5 | 27.08% |
| **Northeast** | 1123.9 | 1283.5 | 1231.9 | 9.61% | 1241.0 | 0.74% | 1194.2 | -6.96% |
| **Northern coast** | 2517.0 | 2451.7 | 2671.6 | 6.14% | 2686.1 | 0.54% | 2331.8 | -4.89% |
| **Eastern coast** | 2685.3 | 2345.9 | 2819.2 | 4.99% | 2853.2 | 1.21% | 2379.4 | 1.43% |
| **Southern coast** | 1519.5 | 1281.8 | 1643.0 | 8.13% | 1658.4 | 0.93% | 1303.0 | 1.65% |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Middle reaches of Yellow River** | 3162.5 | 3361.0 | 3371.0 | 6.59% | 3461.9 | 2.70% | 3120.3 | -7.16% |
| **Middle reaches of Yangtze River** | 1355.8 | 1317.1 | 1503.9 | 10.92% | 1514.3 | 0.70% | 1258.6 | -4.44% |
| **Southwest** | 1254.0 | 1414.5 | 1282.8 | 2.29% | 1346.6 | 4.98% | 1316.4 | -6.94% |
| **Northwest** | 707.8 | 698.7 | 770.1 | 8.81% | 779.1 | 1.16% | 764.6 | 9.44% |
| **China** | 14325.8 | 14154.3 | 15293.6 | 6.76% | 15540.7 | 1.62% | 13668.3 | -3.43% |

Note: * in billion kWh, # in million tonnes of $CO_2$

**Table A3 Synergy effects of spatial and temporal trading of $CO_2$, $SO_2$ and $NO_x$ emission permits (2006-2010 total)**

| **Regions** | **Observed electricity generation in base case*** | **Electricity generation After eliminating technical inefficiency*** | **Electricity generation with spatial and temporal $CO_2$ trading*** | **Electricity generation with spatial and temporal $CO_2$+$SO_2$ trading*** | **Percentage increase in electricity with spatial $CO_2$+$SO_2$ trading** | **Electricity generation with spatial and temporal $CO_2$+$SO_2$+$NO_x$ trading*** | **Percentage increase in electricity with spatial $CO_2$+$SO_2$+$NO_x$ trading** |
|---|---|---|---|---|---|---|---|
| **Beijing** | 117.6 | 118.95 | 119.07 | 119.27 | 0.17% | 121.76 | 2.09% |
| **Tianjin** | 212.8 | 212.80 | 214.39 | 224.97 | 4.94% | 226.11 | 0.51% |
| **Hebei** | 839.5 | 872.44 | 882.95 | 893.74 | 1.22% | 903.88 | 1.13% |
| **Shanxi** | 895.7 | 934.17 | 940.35 | 955.43 | 1.60% | 962.99 | 0.79% |
| **Inner Mongolia** | 974.8 | 1017.39 | 1097.33 | 1108.45 | 1.01% | 1127.38 | 1.71% |
| **Liaoning** | 548.3 | 585.86 | 588.18 | 594.39 | 1.06% | 604.36 | 1.68% |
| **Jilin** | 229.7 | 229.70 | 234.33 | 244.37 | 4.29% | 255.47 | 4.54% |
| **Heilongjiang** | 345.9 | 416.34 | 418.54 | 419.83 | 0.31% | 426.93 | 1.69% |
| **Shanghai** | 395.5 | 395.50 | 395.50 | 399.15 | 0.92% | 416.53 | 4.36% |
| **Jiangsu** | 1408.7 | 1455.40 | 1460.15 | 1467.08 | 0.47% | 1473.85 | 0.46% |
| **Zhejiang** | 881.1 | 968.35 | 997.59 | 999.57 | 0.20% | 1003.37 | 0.38% |
| **Anhui** | 536.8 | 572.35 | 573.25 | 577.89 | 0.81% | 583.21 | 0.92% |
| **Fujian** | 380.4 | 382.15 | 386.75 | 390.75 | 1.03% | 412.67 | 5.61% |
| **Jiangxi** | 215.5 | 250.84 | 252.68 | 252.83 | 0.06% | 256.02 | 1.26% |
| **Shandong** | 1347.1 | 1467.46 | 1469.73 | 1468.55 | -0.08% | 1479.02 | 0.71% |
| **Henan** | 934.8 | 1040.31 | 1042.52 | 1042.32 | -0.02% | 1058.27 | 1.53% |
| **Hubei** | 312.5 | 331.40 | 336.15 | 336.87 | 0.21% | 340.07 | 0.95% |
| **Hunan** | 291.0 | 349.30 | 352.26 | 351.46 | -0.23% | 355.22 | 1.07% |
| **Guangdong** | 1084.5 | 1205.30 | 1214.54 | 1218.85 | 0.35% | 1228.47 | 0.79% |
| **Guangxi** | 196.8 | 196.80 | 196.80 | 205.55 | 4.45% | 206.85 | 0.63% |
| **Hainan** | 54.6 | 55.58 | 57.10 | 58.43 | 2.33% | 61.63 | 5.47% |
| **Chongqing** | 144.5 | 157.64 | 168.47 | 178.67 | 6.05% | 181.95 | 1.84% |
| **Sichuan** | 236.1 | 243.84 | 266.59 | 281.92 | 5.75% | 295.99 | 4.99% |
| **Guizhou** | 437.5 | 443.50 | 445.90 | 452.37 | 1.45% | 468.80 | 3.63% |
| **Yunnan** | 239.1 | 240.98 | 268.87 | 269.10 | 0.08% | 272.02 | 1.08% |
| **Shaanxi** | 357.2 | 379.14 | 381.69 | 387.65 | 1.56% | 391.68 | 1.04% |
| **Gansu** | 228.1 | 254.65 | 256.39 | 257.93 | 0.60% | 259.11 | 0.46% |
| **Qinghai** | 49.3 | 52.89 | 54.01 | 54.67 | 1.22% | 55.58 | 1.66% |
| **Ningxia** | 226.8 | 226.80 | 226.82 | 226.81 | 0.00% | 228.92 | 0.93% |
| **Xinjiang** | 203.6 | 235.81 | 241.83 | 247.68 | 2.42% | 252.14 | 1.80% |
| **Northeast** | 1123.90 | 1231.90 | 1241.05 | 1258.59 | 1.41% | 1286.76 | 2.24% |
| **Northern coast** | 2517.00 | 2671.65 | 2686.15 | 2706.54 | 0.76% | 2730.78 | 0.90% |
| **Eastern coast** | 2685.30 | 2819.25 | 2853.23 | 2865.79 | 0.44% | 2893.75 | 0.98% |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Southern coast** | 1519.50 | 1643.03 | 1658.39 | 1668.03 | 0.58% | 1702.77 | 2.08% |
| **Middle reaches of Yellow River** | 3162.50 | 3371.00 | 3461.89 | 3493.86 | 0.92% | 3540.31 | 1.33% |
| **Middle reaches of Yangtze River** | 1355.80 | 1503.88 | 1514.34 | 1519.05 | 0.31% | 1534.52 | 1.02% |
| **Southwest** | 1254.00 | 1282.76 | 1346.64 | 1387.62 | 3.04% | 1425.60 | 2.74% |
| **Northwest** | 707.80 | 770.14 | 779.06 | 787.10 | 1.03% | 795.75 | 1.10% |
| **China** | 14325.80 | 15293.61 | 15540.75 | 15686.59 | 0.94% | 15910.24 | 1.43% |

Note: * in billion kWh