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Co-Benefits of Integrating PM_{10} and CO_2 Reduction in an Electricity Industry in Tianjin, China

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ABSTRACT

Based on the actual PM_{10} and CO_2 emissions in 2010, and the projected situation in 2015, this study assesses the co-benefits of the Local Air Particulate Matter (LAP) reduction plan and Greenhouse Gas (GHG) control plan in a coal-fired power industry in Tianjin, China. This co-benefit analysis used the Ambient Least Cost Model (ALC) to estimate PM_{10} and CO_2 emission reduction and cost, then developed a PM_{10} and CO_2 control technologies inventory. The results show that a rebuilt bag-house precipitator in 300 MW units is most cost-effective method of reducing PM_{10} emissions in a thermal power plant. In contrast, CCS-MEA is the most effective option for reducing CO_2 emissions in the existing plant. The results of the cost-benefit analysis indicated that using a Nuclear Power plant is the most cost effective way to reduce PM_{10} and CO_2 emissions at the same time, but IGCC is a safer choice for Tianjin. The integrated environmental strategy (IES) scenario presented in this work makes it possible to reduce CO_2 emissions by 28,095,386 t and PM_{10} emissions by 35,930.73 t, at a cost of 9.69 billion Yuan from 2010 to 2015, which is better than both suggested targets (ST) for PM_{10} and CO_2 during the Twelfth Five-Year Plan.

Keywords: PM_{10} reduction potential; CO_2 reduction; Cost-benefit analysis; Co-benefits.

INTRODUCTION

Like many countries, China is trying to balance environmental and global climate change concerns against economic growth. Previous government policies to improve air quality in Tianjin have achieved remarkable outcomes. However, many measures have reached their limits of effectiveness due to the rapidly economic development in China. Recognition of these serious challenges led to the formal announcement of action reduction target control that cut carbon emission 40%–45% per unit in GDP by 2020 in comparison with that of 2005 by Premier Wen Jiabao in 2009. In addition to aggressively pursuing improved air quality, China has joined international efforts to reduce greenhouse gases (GHGs) by attending the United Nations Framework Convention on Climate Change (UNFCCC) in Durban, South Africa Nov. 28, 2011.

More recently, the Chinese government announced a GHG reduction target of cutting 17% of CO_2 and 16% of energy consumption per unit in GDP, increasing 3.1% (from 8.3% to 11.4%), non-fossil energy consumption, and reducing total emissions of major pollutants from 8% to 10% by 2015 in the General Plan of Save Energy and Reduce Emission in the Twelfth Five-Year Plan. The consensus-building process will be based on a mitigation potential study conducted by key research institutions that will set out three mitigation scenarios options for 2015. This co-benefits analysis is based on the current price of GDP in Tianjin in 2010 as the base year and 2015 as the target year.

For China, implementing integrated measures that address both Local Air Particulate Matter (LAP) and Greenhouse Gas (GHG) is essential to achieving necessary air pollution reductions and preparing for future agreements on climate change. Integrated strategies have been implemented worldwide as cost-benefit mechanisms to reduce LAP and GHG which are co-generated by the combustion of fossil fuels. Previous co-benefit studies have shown that GHG mitigation policies have had a positive effect on regional air quality (Van Vuuren *et al.*, 2006; Rypdal *et al.*, 2007; Williams, 2007), though relatively few studies available document how air quality management affects GHG emissions (Xu and Masui, 2009) and how tackling both problems could be optimized. Based on cost effectiveness, this study develops an alternative scenario for emission reduction measures through optimization in order to achieve both air quality improvements and GHG reduction targets at a minimum cost.

METHODS

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Sampling Sites and Description

Tianjin is one of China's four municipalities, rapidly economic growth has contributed to serious air quality problems to Tianjin. Like many other cities in the world, the air pollution and greenhouse gas emission in Tianjin are largely associated with the energy activities (fossil fuels burning). Major sources for CO_2 emission in Tianjin are shown in Fig. 1.

As shown in the Fig. 1, industry and electricity generation were the first two sources in the area of energy activities, which ratios were separately 44% and 41% in all greenhouse gas emission. Therefore, Tianjin may reduce greenhouse gas emission based on the adjustment of energy structure, the improvement of reduction technology of coal-fired power industry. In 2010, there were 11 coal-fired companies and plants in electricity generation industry in Tianjin (see Table 1). The total CO_2 emission of coal-fired power industry in Tianjin 2010 was 61,800 t, while the total PM_{10} emission was 161.472 t. Average $M_{2.5}$ and PM_{10} mass levels in Tianjin, China, from September 2009 to February 2010, were 124 and 243 μg/m^3, with 53% of the PM_{10} mass present as $PM_{2.5}$. Secondary organic carbon was found to constitute 46% and 66% of the total organic carbon in $PM_{2.5}$ and PM_{10}, respectively, in autumn and 41% and 56%, respectively in winter.

In 2012, emission standard of air pollutants for thermal power plants was emended. GB13223-2011 issued a new emission limitation of PM_{10}, using 30 mg/m^3 instead of 50 mg/m^3 which issued in 2003. For the current standard emendation, new establishment of coal-fired power plant must follow the new standard of air pollutant emission limitations. To reach the new emission standard, existing plants and new plants need a 40% migration potential through improving clean technologies in 2015.

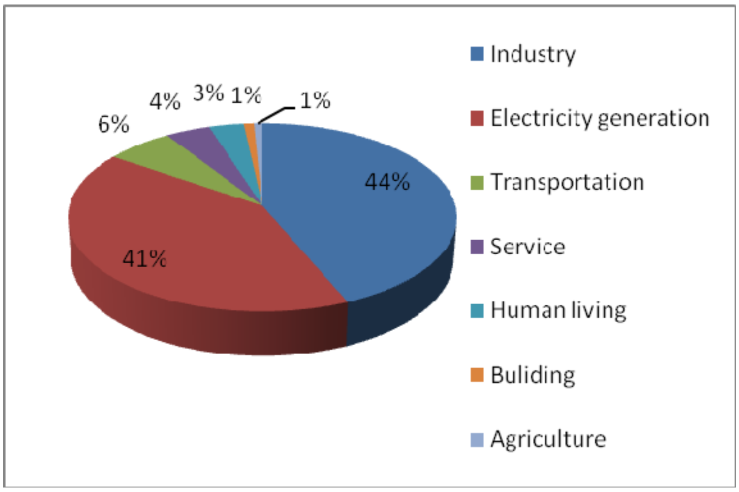

Fig. 1. Major sources CO_2 emission in Tianjin, China 2010.

Table 1. The current Thermal Power Plants status of Tianjin in 2010.

	Tianjin Power Plant Company	Unit and Situation
1	Da gang Power Plant	1992 328.5 MW × 2 (No. 3, 4) 2005 328.5 MW × 2 (No. 1, 2)
2	First Heat Power Plant	1989 50 MW × 4 (No. 8–11)
3	Jun Liang-cheng Power Plant	1989 200 MW (No. 6) 1992 200 MW (No. 7) 1998 200 MW (No. 5) 1971 100 MW × 2 (No. 1, 2) 2010 350 MW × 2 (No. 9, 10)
4	Yang Liu-qing Heat Power Plant	1999 300 MW × 2 (No. 5, 6) 2007 300 MW × 2 (No. 7, 8)
5	Datang Int. Panshan Power Plant	2002 600 MW × 2 (No. 3, 4)
6	Guohua Panshan Power Plant	1996 500 MW × 2 (No. 1, 2)
7	Chentang Heat Power Plant	2008 300 MW × 2 (No. 8, 9) 2001 50 MW (No. 3, 4)
8	Beijiang Power Plant (USC)	2010 1000 MW × 2 (No. 1, 2)
9	Tianjin Dongbeijiao Power Plant	2009 330 MW × 2 (No. 1, 2)
10	Huaneng Green Power Plant (IGCC)	2010 250 MW (No. 1)
11	First Project, Beitang Power Plant (SC)	2010 350 MW × 2 (No. 1, 2)

Note: The numbered symbols No. refers to the unit order number in each plant.

China's GHG emission target is 40%–45% reduction in per unit GDP carbon dioxide emissions in 2020, based on the 2005 level. The emission target of Tianjin was set at an additional 18% reduction of Energy Consumption per unit of GDP during the Twelfth Five-Year Plan. The emission target of Tianjin was set at an additional 19% reduction of CO_2 emission per unit of GDP during the Twelfth Five-Year Plan. Therefore, the yearly reduction target of Energy Consumption per unit of GDP in Tianjin is an average of 3.9%. The years 2010 and 2015 are chosen as the control target years in alignment with the national planning for social and economic development every five years in China. The 11^{th} Five Year Plan ends in 2010 and the 12^{th} Five Year Plan will end in 2015. In 2011, the Tianjin National Economic and Social Development Plan in the Twelfth Five-Year Plan announced that the reduction target of Energy Consumption per unit of GDP is 4%.

In 2010, the fire coal consumption was 49,000,000 t, the total prospected energy consumption in 2015 will be 109,960,000 t and standard coal in Tianjin, in which fire coal is 73,680,000 t (50.37% increased from 2010). There will be an additional 24,680,000 t. increase of fire coal by 2015, in which 18,980,000 t. in power industry and an additional 5,700,000 t. in non-electric power industry. The 2015 prospected total coal consumption in power industry is 20,610,000 t., including 18,980,000 t. (92.1%) in power industry and 1,630,000 t. (7.9%) from closing down backward production facilities.

Ambient Least Cost Model (ALC)

Emissions of air pollutants from various source categories were estimated using methodologies and emission factors from the Research on Co-benefits of Integrating Urban Air Particulate Matter Reduction and Climate Change Final Report (2011). Stationary source emissions were estimated using emission factor, coal consumption, and air pollutant removal efficiency. This study used the Ambient Least Cost Model (ALC) to estimate the unit cost of each measure.

The ALC Model was first proposed by Atkinson and Lewis (1974). It minimizes the cost of different sectors' pollution control techniques in different areas under set constraints and targets. This optimization model was developed to identify the most cost effective measure to meet the target emissions of PM_{10} and CO_2. The equations for the optimization model are as follows:

$$MinC = \sum_{i=1}^{N}\sum_{t=1}^{Ti}\left(\left(u_i \times e_{i,t}\right)\times c_{i,t} \times x_{i,t}\right) \tag{1}$$

Subject to:

$$\begin{aligned} &\psi\left[u,e,x\right] \geq S_j,\ \forall j = 1, M \\ &x_{i,t} \in \{0, 1\};\ \forall i = 1, M;\ t = 1, T_i \\ &\sum_{t=1}^{Ti} x_{i,t} = 1,\ \forall i = 1,\ N \end{aligned} \tag{2}$$

Indexes, sets and parameters: C = Total cost; i = Emission source; N = the Number of Emission source; t = Technology; T_i = Technologies can choose by Emission Source i; u_i = the Emission level of Source i without any measure; $e_{i,t}$ = the technology removal efficiency to Emission Source i; $c_{i,t}$ = the unit cost of technology t to Emission Source i; $x_{i,t}$ = a dummy, when the Emission Source i use the technology t then $x_{i,t}$ = 1; if not use it, then $x_{i,t}$ = 0; j = control zone; M = the Number of control zone; u = the collection of all sources; e = the collection of all emission reduction measures; x = the utility of all control measures; ψ the function of proposed emission change in control zone; S_j = emission reduction target of control zone j.

Objective function (1) minimizes the total cost for abating emissions of PM_{10} or CO_2. Constraint (2) shows the control target, which means the atmospheric pollutant concentration in the recipient location, will not increase more than the reduction targets. Constraints (2) also specify that each source can only adopt one control option.

This study also estimated the unit cost of each measure ($UC_{i,xi}$), which is the summation of technology cost and reduction potential quantity. Technology cost generally includes the investment costs ($IC_{i,xi}$), fixed operation costs ($FC_{i,xi}$) and variable operation costs ($VC_{i,xi}$). The investment costs ($IC_{i,xi}$) include the expenditure accumulated until the start-up of an installation, such as delivery of the installation, construction, civil works, ducting, engineering and consulting, license fees, land requirement and capital. The equation uses investment functions where these cost components are aggregated into one function. The shape of the function is described by its coefficients investment costs, fixed operation costs and variable operation costs. Technology Cost was converted to Annual Technology Cost ($ATC_{i,xi}$) with equipment longevity to estimate future unit cost more accurately. The equation for converting equipment cost to $ATC_{i,xi}$ is shown in Eq. (4). $FC_{i,xi}$ is the annual equate fixed operation cost of technology; as well as $VC_{i,xi}$ is the annual variable operation cost of the measure.

Annual Reduction Potential Quantity ($CQ_{i,xi}$):

$$CQ_{i,xi} = Q_{i,xi} \times \gamma_{i,xi} \tag{3}$$

$CQ_{i,xi}$ is the Annual PM_{10} or CO_2 Reduction Potential Quantity of reduction technology; $Q_{i,xi}$ is the PM_{10} or CO_2 Emission of power plant in 2010; $\gamma_{i,xi}$ is the air pollutant removal efficiency. i = emission source; xi = technologies can choose by Emission Sources i.

Annual Average Technology Cost ($ATC_{i,xi}$):

$$ATC_{i,xi} = IC_{i,xi}^{an} + FC_{i,xi} + VC_{i,xi} \tag{4}$$

$ATC_{i,xi}$ = annual average technology cost, $IC_{i,xi}^{an}$ = the annualized investments. The investments were annualized over the technical lifetime of plants (n), using the real interest rate in percentage (γ) shown as CRF in Eq. (5). $FC_{i,xi}$ = the annual fixed operation cost of technology. The fixed operation cost is a standard percentage of the total investment. $VC_{i,xi}$ = the annual variable operation cost of the measure. The variable operation costs of different technologies are related to electricity demand, energy price and repair fee etc. i = emission source; xi = technologies can choose by Emission Source i.

$$CRF = \frac{\gamma(\gamma+1)^n}{(\gamma+1)^n - 1} \quad (5)$$

$$IC_{i,xi}^{an} = IC_{i,xi} \times CRF \quad (6)$$

CRF = annualize coefficient. $IC_{i,xi}$ =investment costs; n = technical lifetime; γ = real interest rate in percentage. The real interest rate (γ) used in this study is 6%, which is the average loan interest rate in 2010. i = emission source; xi = technologies can choose by Emission Source i.

Unit Reduce Cost ($UC_{i,xi}$) is defined as the average abatement cost of the technology which denotes the average cost per unit of PM_{10} or CO_2 is reduced:

$$UC_{i,xi} = \frac{ATC_{i,xi}}{CQ_{i,xi}} \quad (7)$$

Scenario Description

This scenario analysis is based on the ALC model where abundant bottom-up technologies have been included. Policies that are implemented in different scenarios are assumed to affect the adoption of specific technologies. The scenario analysis timespan covers the years 2010–2015 with 2010 as the baseline year.

There are one business as usual (BAU) scenario and three generated scenarios in this study, including Local Air Pollutant (LAP) scenario, Greenhouse Gas (GHG) scenario and Integrated Environmental Strategy (IES) scenario. BAU scenario is the situation without any reduction measure. In LAP scenario, this paper assumed that only use PM_{10} reduction technology while the GHG scenario only utilize CO_2 reduction technology. Based on cost-benefit analysis, this study developed an integrated environmental strategy (IES) to achieve air quality improvement and CO_2 reduction with a minimum cost in Tianjin. Different Scenarios share the same assumptions for gross domestic product to avoid uncertainty when forecasting production.

RESULTS AND DISCUSSION

Cost-benefit Analysis

To achieve the 2015 reduce target, extensive measures have been implemented and planned in order to improve air quality in Tianjin. PM_{10} Emission control techniques can be categorized as Bag-house Precipitator, Electrostatic Dust Precipitator and Electrostatic-bag house Integrated Precipitator. The differences of dust precipitators are shown in Table 2. The cost and reduce potential of power plants are given separately for three capacity classes: 200 MW, 300 MW and 600 MW. CO_2 Emission control technologies include: Integrated Gasification Combined Cycle Power Plant (IGCC), Ultra-Supercritical Power Plant (USC), Supercritical Power Plant (SC), Nuclear Power Plant(NUCLEAR), Wind Power Plant (WIND), Solar Energy Photovoltaic Plant (SOLAR), Biomass Power (BIOMASS), CO_2 capture and storage (CCS), Mono Ethanol Amine solvents capture and storage (CCS-MEA) and Flue Gas Desulphurization (FGD). Physical adsorption is most suitable for CO_2 capture at high pressures and low temperatures, it is therefore not particularly applicable for the post-combustion CO_2 capture. On the other hand, chemically modified adsorbents have been proved to be feasible. As the capacity and age of the power generators are different even in one power plant, PM_{10} and CO_2 control and emission reduction costs may be different. So we analyzed each plant unit and categorized them by typical production capacity.

Some measures are end-of-pipe measures which do not have co-benefits, while other measures have both air pollutants and CO_2 emission reduction effects such as switching SC plant to IGCC plant and increasing the use of renewable energy. Because cost is one of the key factors for determining the effectiveness of the measures, a cost-benefit analysis was conducted to identify measures most effective in reducing air pollutant and GHG emissions

Fig. 2 and Fig. 3 show cost effectiveness for PM_{10} and CO_2 in Tianjin Thermal Power Plant Industry. It has been found that Rebuild Bag-house Precipitator 300 MW is the most cost effective end-of-pipe measure in PM_{10} emission reduction. Using MEA-CO_2 capture and storage (CCS-MEA) technology is the most cost effective end-of-pipe measure in CO_2 emission reduction. For switching the plant type, Nuclear Power 1000 MW is the best cost-beneficial choice to replace the ordinary power plant.

Co-benefit Analysis

To see each of the LAP and GHG measures' co-benefit, the correlation between air pollutants and CO_2 emission reduction for each measure was analyzed. Correlations for PM_{10}-CO_2's cost-benefit regarding the measures are presented in Figs. 4–8.

Conducted the Ambient Least Cost model by control options indentified in this study, we got the results of optimal route of cost effective control. Fig. 9 shows the optimization results of annual PM_{10} reduction potential and unit CO_2 reduce cost of typical technologies which are formed by control measure options. Fig. 10 expresses the optimization results of CO_2 typical technologies. The unit reduces cost is the marginal cost, increasing as technologies are implemented one by one. The unit for annual reduce

Table 2. Suitable Condition and PM_{10} Reduction Efficiency of Technologies.

PM_{10} reduce Technology	Suitable Condition	PM_{10} Reduce Efficiency
Bag-house Precipitator	Emission level < 30 mg/m^3	> 99.9%
Electrostatic Dust Precipitator	Emission level < 50 mg/m^3	99.5%~99.8%
Electrostatic-bag house Integrated Precipitator	Emission level < 30 mg/m^3	> 99.9%

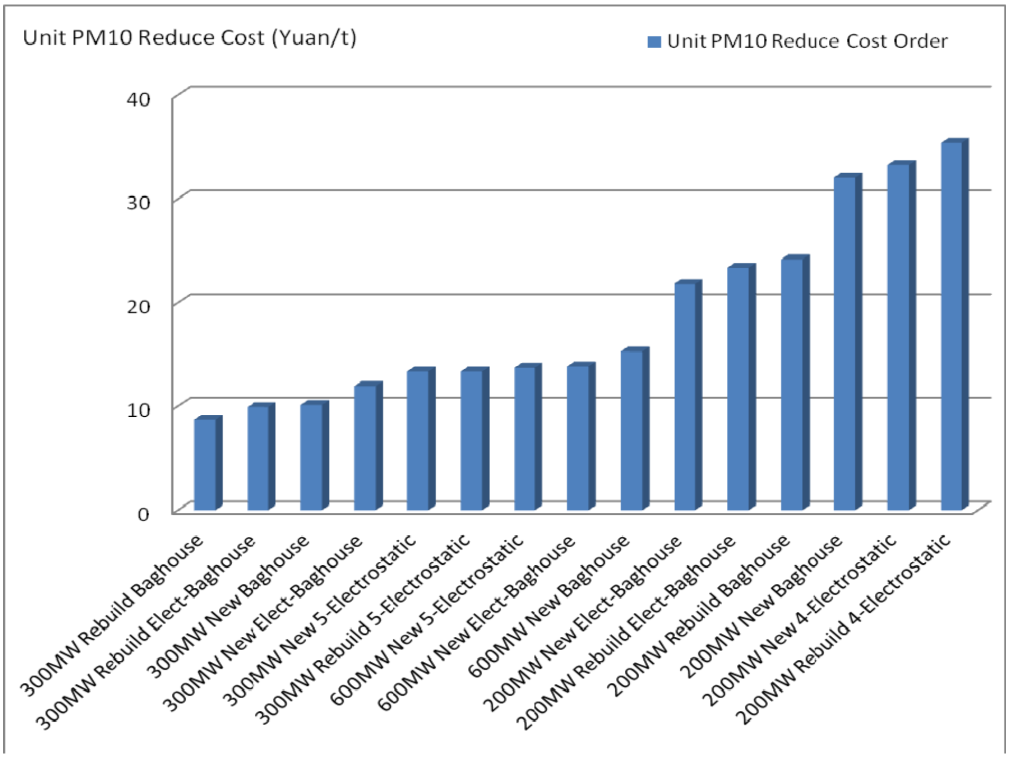

Fig. 2. PM_{10} emission reduction measures' cost-effectiveness Order.

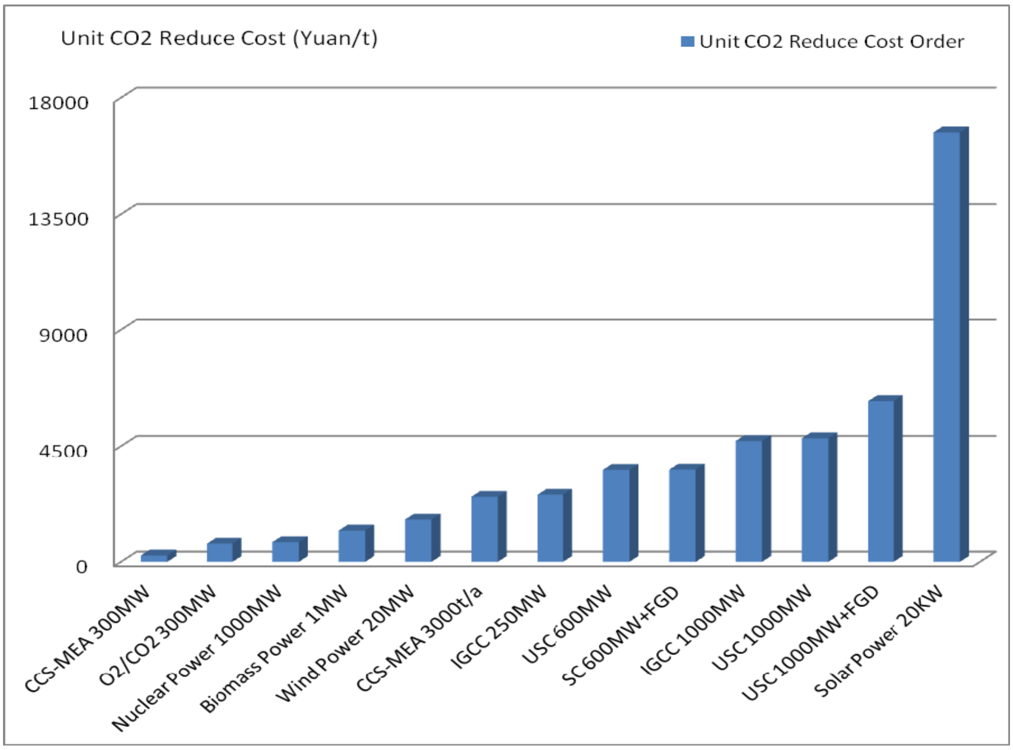

Fig. 3. CO_2 emission reduction measures' cost-effectiveness Order.

potential is ton (t) and the unit for the annual average cost is million Yuan (RMB).

The results showed that: the correlation of the cost-benefit analysis indicated that adding FGD on existing plants is the most PM_{10} cost effective option for PM_{10}-CO_2 Co-reduce Technology. For switching new energy, nuclear power plant is the most CO_2 cost effective option for PM_{10}-CO_2 co-reduction, as well as biomass energy is the second choice.

The first choice nuclear power is a sustainable energy source that reduces carbon emissions. On the one hand, nuclear power produces virtually little conventional air pollution, such as greenhouse gases and air pollutants, in contrast to the cheap viable alternative of fossil fuel. Nuclear power can produce base-load power unlike many renewable which are intermittent energy sources lacking large-scale and cheap ways of storing energy. On the other hand, compared to the second choice biomass energy, processing, transport and storage of radioactive nuclear waste are too dangerous to Tianjin and Beijing.

The second choice Biomass energy comes from biological

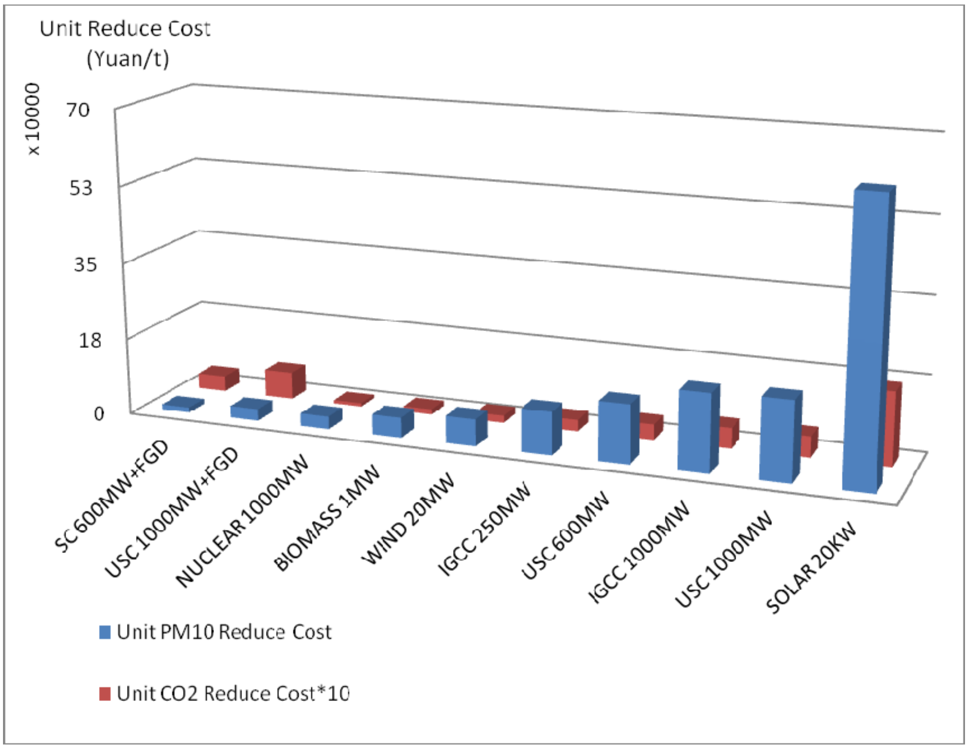

Fig. 4. Unit PM_{10} Reduce Cost Order of PM_{10}-CO_2 Co-reduce Technology (PM_{10} reduce options).

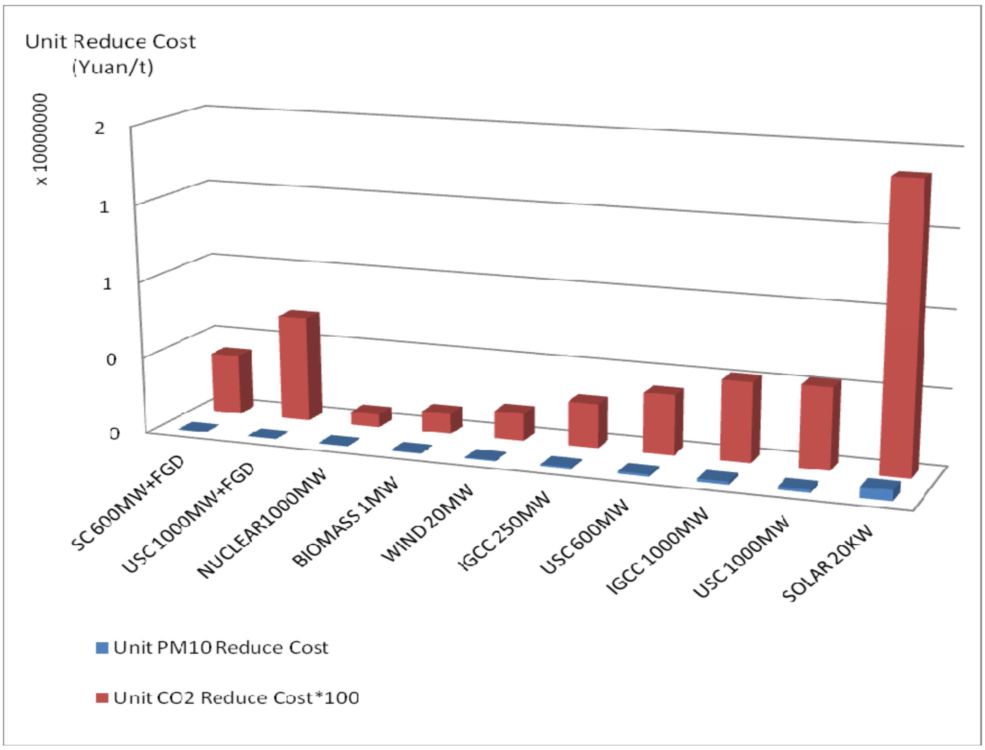

Fig. 5. Unit CO_2 Reduce Cost of PM_{10}-CO_2 Co-reduce Technology as Ordered in Fig. 4 (PM_{10} reduce options).

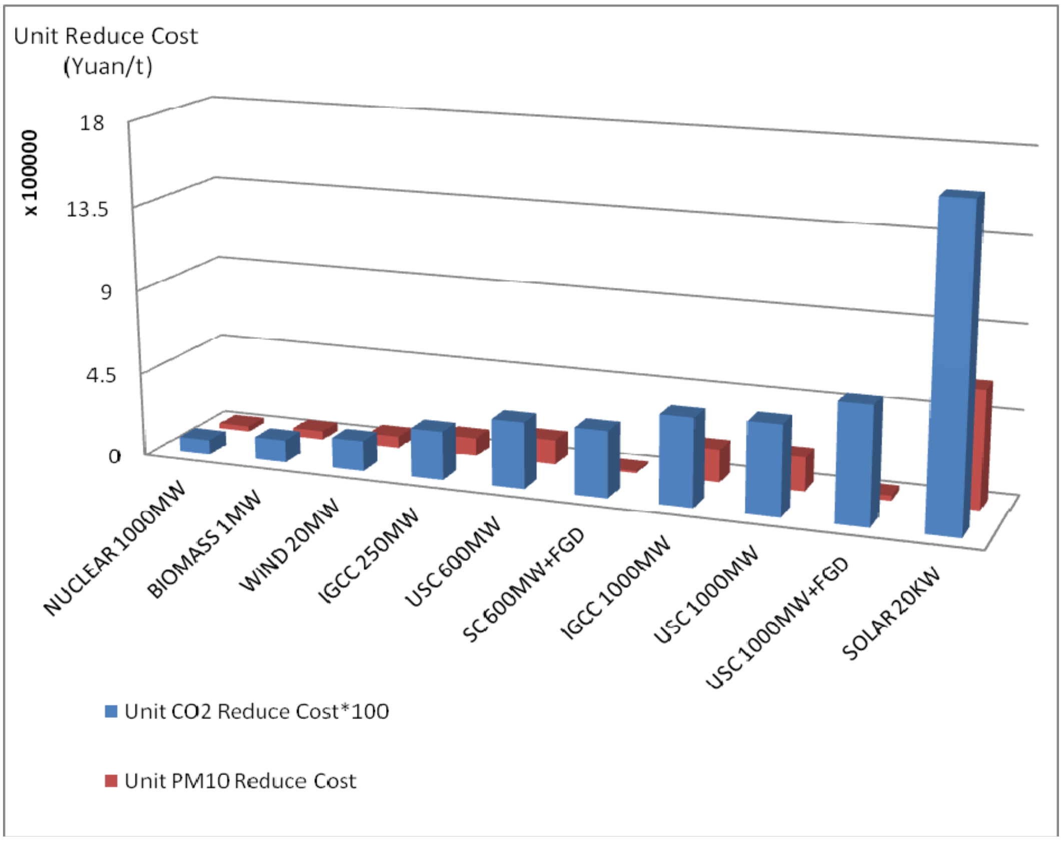

Fig. 6. Unit CO_2 Reduce Cost Order of PM_{10}-CO_2 Co-reduce Technology (CO_2 reduce options).

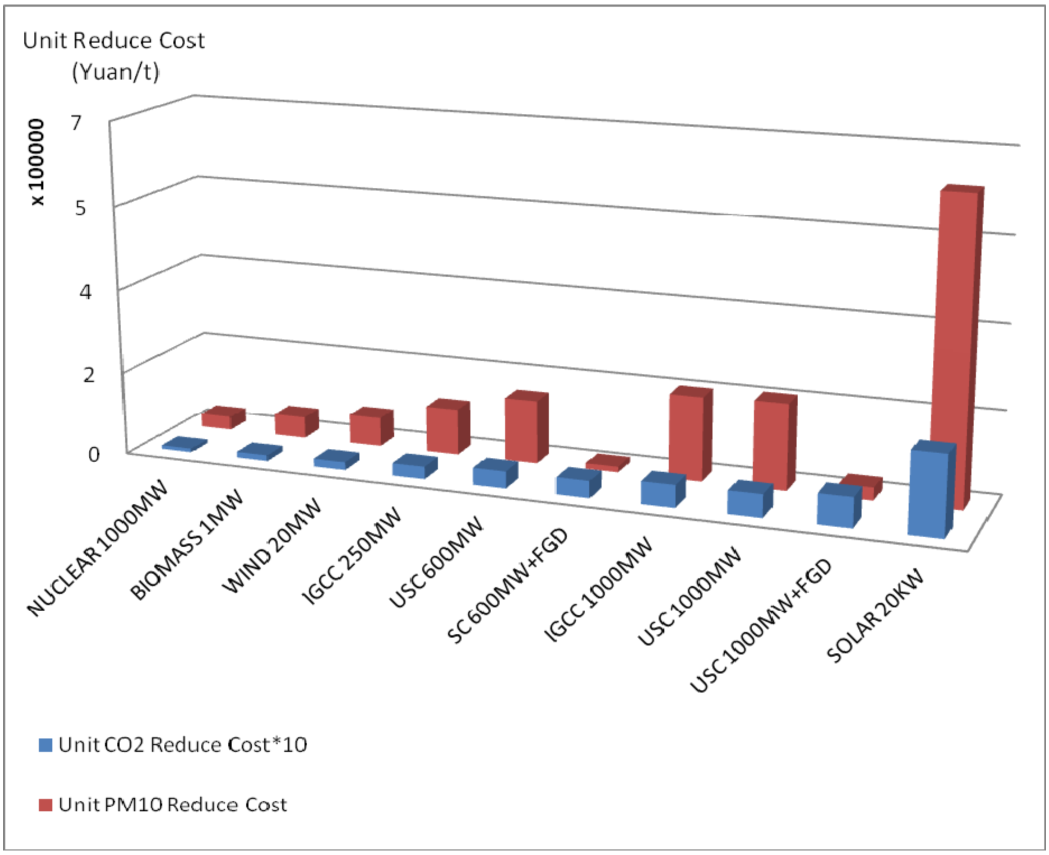

Fig. 7. Unit PM_{10} Reduce Cost of PM_{10}-CO_2 Co-reduce Technology as Ordered in Fig. 6 (CO_2 reduce options).

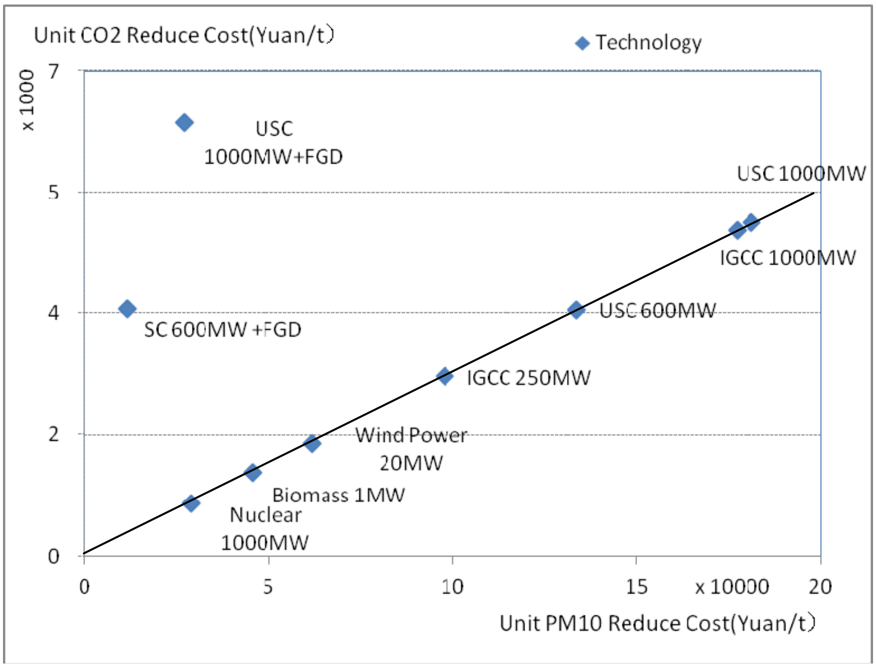

Fig. 8. Correlation of each measure's CO_2 and PM_{10} emission reduction cost-efficiency.

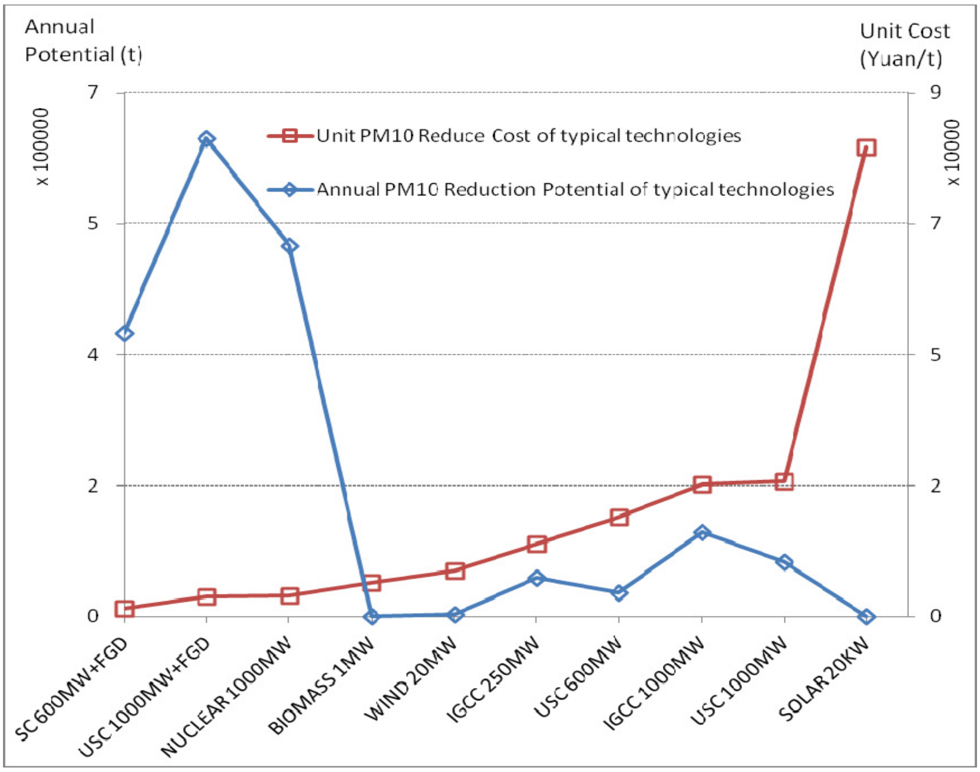

Fig. 9. Optimization results: Annual PM_{10} reduction potential curve of typical technologies and unit PM_{10} reduce cost curve formed by control measure options.

material from living, or recently living organisms. As an energy source, biomass can either be used directly, or converted into other energy products such as biofuel. Some people would argue that the use of biomass would be carbon neutral because trees absorb carbon dioxide to grow. However, in order to fulfill the energy requirements of a large proportion of a nation based on biomass, a large proportion of the land area would have to be planted to biomass forest. To obtain the same electricity from biomass as from a single nuclear power plant would require thousands square kilometers of land working at optimal efficiency. For switching new energy in the big city like

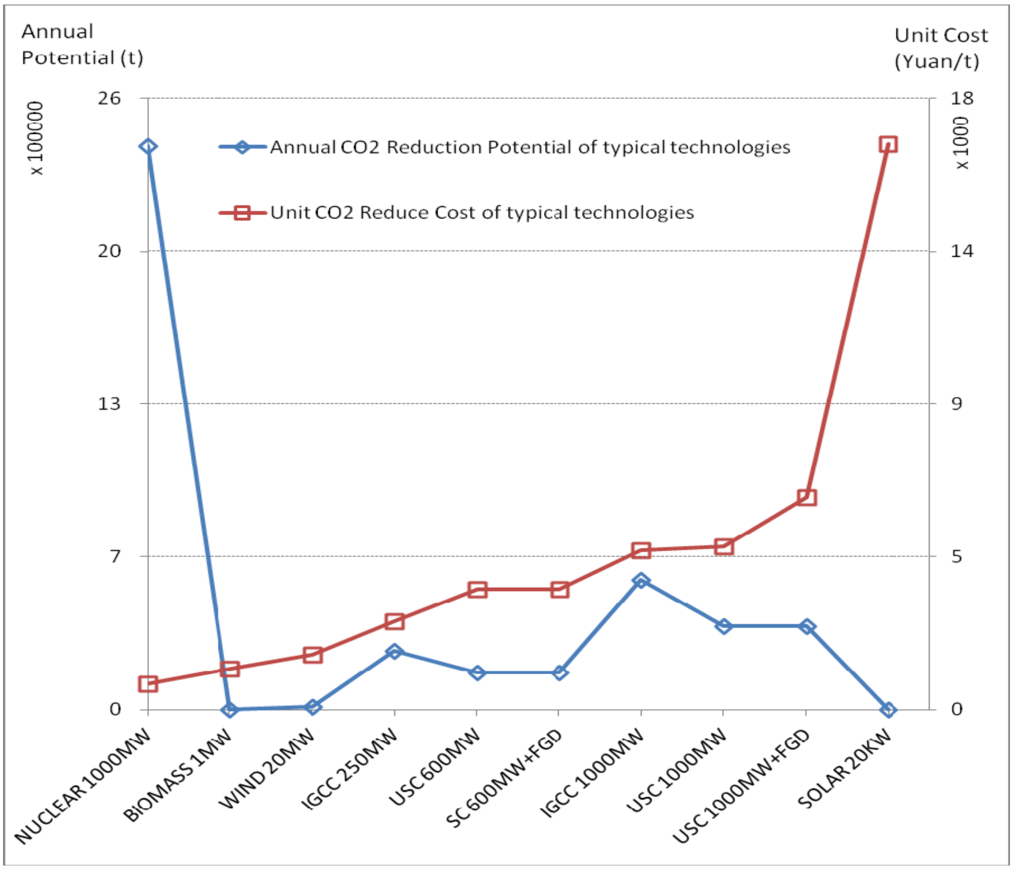

Fig. 10. Optimization results: Annual CO_2 reduction potential curve of typical technologies and unit CO_2 reduce cost curve formed by control measure options.

Tianjin, biomass is not a better choice than IGCC plant and nuclear power plant. The installed capacity and efficiency of biomass energy and wind power energy is too small to a city which has ten million people. Compared to the other renewable sources of energies like solar, wind and tidal, we have to prefer nuclear power for its higher performance to small county town near the sea.

According to the risks of storing waste and nuclear explosion are very important for big city like Tianjin and Beijing, so the fourth option IGCC is a better choice than nuclear power plant in 2010–2015. Though the benefit of biomass energy instead of nuclear only has a slight difference in the cost-efficiency as presented in Fig. 8 and the renewable alternative would provide minor risks, Non-conventional energy sources are only suitable for a certain limit use.

Scenario Analysis

BAU scenario is the situation without any reduction measure. In LAP scenario, this paper assumed that only use PM_{10} reduction technology while the GHG scenario only utilize CO_2 reduction technology. Based on cost-benefit analysis, this study developed an integrated environmental strategy (IES) to achieve air quality improvement and CO_2 reduction with a minimum cost in Tianjin. Four scenarios definition in 2015 was shown in Table 4.

According to the optimized cost-benefit and co-benefit analysis result illustrated in Figs. 9–10, the optimized mitigation options of LAP, GHG scenario to reduce PM_{10} and CO_2 separately for existing coal-fired plants in Tianjin were shown in Table 5 and Table 6. Table 7 showed the optimized co-benefit mitigation suggestions in IES scenario for existing coal-fired plants and possible new plant suggestions in Tianjin. In 2010, there were 11 coal-fired companies and plants in electricity generation industry in Tianjin. Some plants and units were built recently and have advanced mitigation measures and limited reduction potential, thus we choice 7 plants for each scenario.

In scenario optimization, Figs. 11–13 shown the annual reduction potential curves and unit reduce cost curves of LAP, GHG and IES scenarios, which are formed by power plant options. Detailed information about cost and emission reduction of each option is given in Figs. 11–13, from which we could find out the least-expensive mitigation option and the option which is the biggest contributor to emission reduction.

As a result, close 50 MW units First Heat Power Plant is the most cost-beneficial choice in three scenarios. It illustrate that the "keep and promote the large plants, hold or close down the small plants" policy in China is co-beneficial and recommend as the first option for thermal industry.

In LAP scenario, considering the GB13223-2011 issued a new emission limitation of PM_{10}, using 30 mg/m^3 instead of 50 mg/m^3, the suggested target scenario (ST) of PM_{10} migration potential is set as 40%. According to this target,

Table 3. Unit Costs of LAP and GHG co-reduction measures and unit reduction costs.

Technology	Unit PM_{10} Reduce Cost (Yuan/t)	Unit CO_2 Reduce Cost (Yuan/t)
USC 600 MW	133689.466	3551.90
USC 1000 MW	181093.033	4811.33
IGCC 1000 MW	177054.316	4704.03
IGCC 250 MW	97789.3606	2598.09
SC 600 MW + FGD	11564.9886	3562.27
USC 1000 MW + FGD	26885.8404	6246.61
NUCLEAR 1000 MW	28655.8276	761.34
WIND 20 MW	61483.4773	1633.51
SOLAR 20 KW	45502.7099	1208.93
BIOMASS 1 MW	627205.808	16663.77

Table 4. Four scenarios definition in 2015.

Scenario	Situation
BAU	Business as usual, without any reduction measure
LAP	Only use PM_{10} reduction technology
GHG	Only use CO_2 reduction technology
IES	Integrated environmental strategy

Table 5. The mitigation options of LAP scenario.

Coal-fired Power Plant	Unit (MW)	Mitigation options
First Heat Power Plant	50 × 4	Close 50 MW units
Chentang Heat Power Plant	50 × 2, 300 × 2	Close 50 MW units and retrofit Bag house Precipitator on 300 MW units
Jun Liang-cheng Power Plant	100 × 2, 200 × 4	Close 100 MW units and retrofit Electrostatic-bag house Integrated Precipitator on 200 MW units
Yang Liu-qing Heat Power Plant	300 × 2	Retrofit Bag house Precipitator on 300 MW units
Datang Int. Panshan Power Plant	600 × 2	Retrofit Electrostatic-bag house Integrated Precipitator on 600 MW units
Guohua Panshan Power Plant	500 × 2	Retrofit Electrostatic-bag house Integrated Precipitator on 500 MW units
Da gang Power Plant	328.5 × 4	Retrofit Bag house Precipitator on 300 MW units

Table 6. The mitigation options of GHG scenario.

Coal-fired Power Plant	Unit (MW)	Mitigation options
First Heat Power Plant	50 × 4	Close 50 MW units
Chentang Heat Power Plant	50 × 2, 300 × 2	Close 50 MW units and retrofit CCS-MEA on 300 MW units
Jun Liang-cheng Power Plant	100 × 2, 200 × 4	Close 100 MW units and retrofit CCS-MEA on 200 MW units
Yang Liu-qing Heat Power Plant	300 × 2	Retrofit CCS-MEA on 300 MW units
Datang Int. Panshan Power Plant	600 × 2	Retrofit CCS-MEA on 600 MW units
Guohua Panshan Power Plant	500 × 2	Retrofit CCS-MEA on 500 MW units
Da gang Power Plant	328.5 × 4	Retrofit CCS-MEA on 300 MW units

Table 7. The mitigation options of IES scenario.

Coal-fired Power Plant	Unit (MW)	Mitigation options
First Heat Power Plant	50 × 4	Close 50 MW units
Chentang Heat Power Plant	50 × 2, 300 × 2	Close 50 MW units, retrofit CCS-MEA and retrofit Bag house Precipitator on 300 MW units
	900 × 2	Bulid new USC units
Jun Liang-cheng Power Plant	100 × 2, 350 × 2	Close 50 MW units, Bulid New 350 MW SC units and add Flue Gas Desulphurization (FGD)
Yang Liu-qing Heat Power Plant	600 × 2	Bulid new USC units
Beijiang Power Plant (USC)	1000 × 2	Bulid new USC units
Second Project, Huaneng Green Power Plant (IGCC)	250	Bulid new IGCC units
First Project, Beitang Power Plant	350 × 2	Bulid new USC units

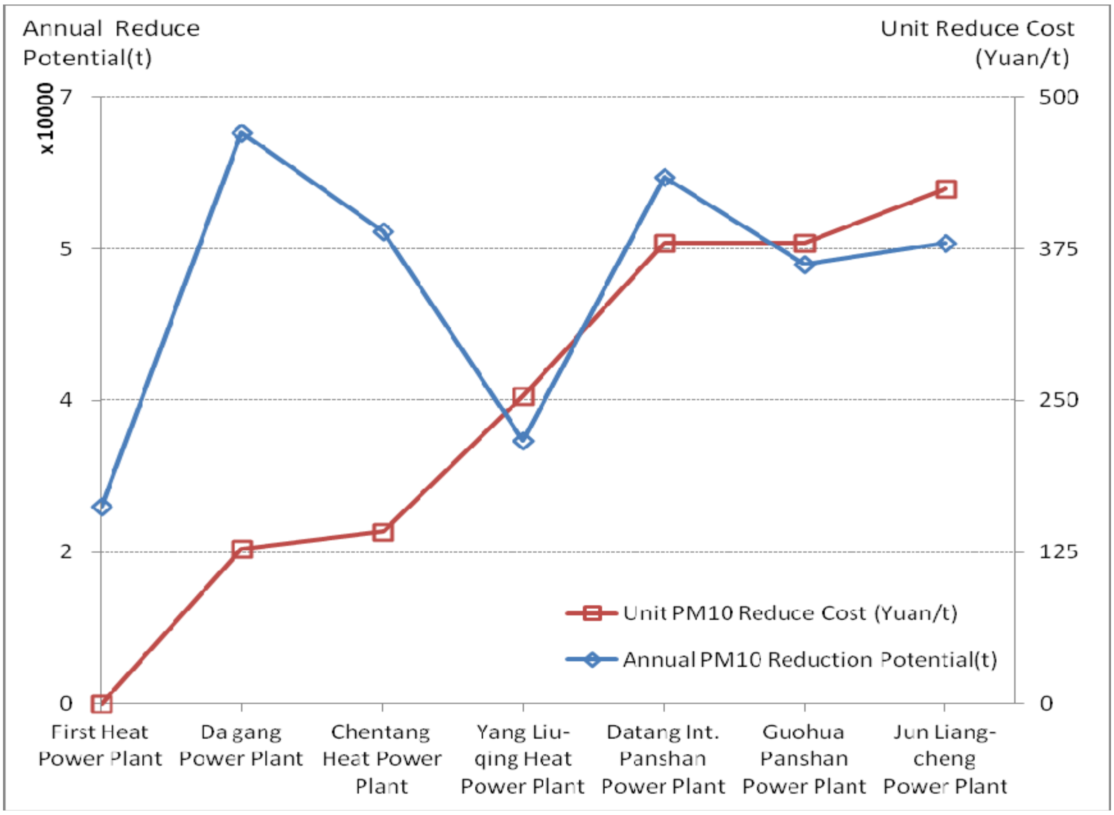

Fig. 11. LAP Scenario optimization results: Annual PM_{10} reduction potential curve and unit PM_{10} reduce cost curve formed by power plant options.

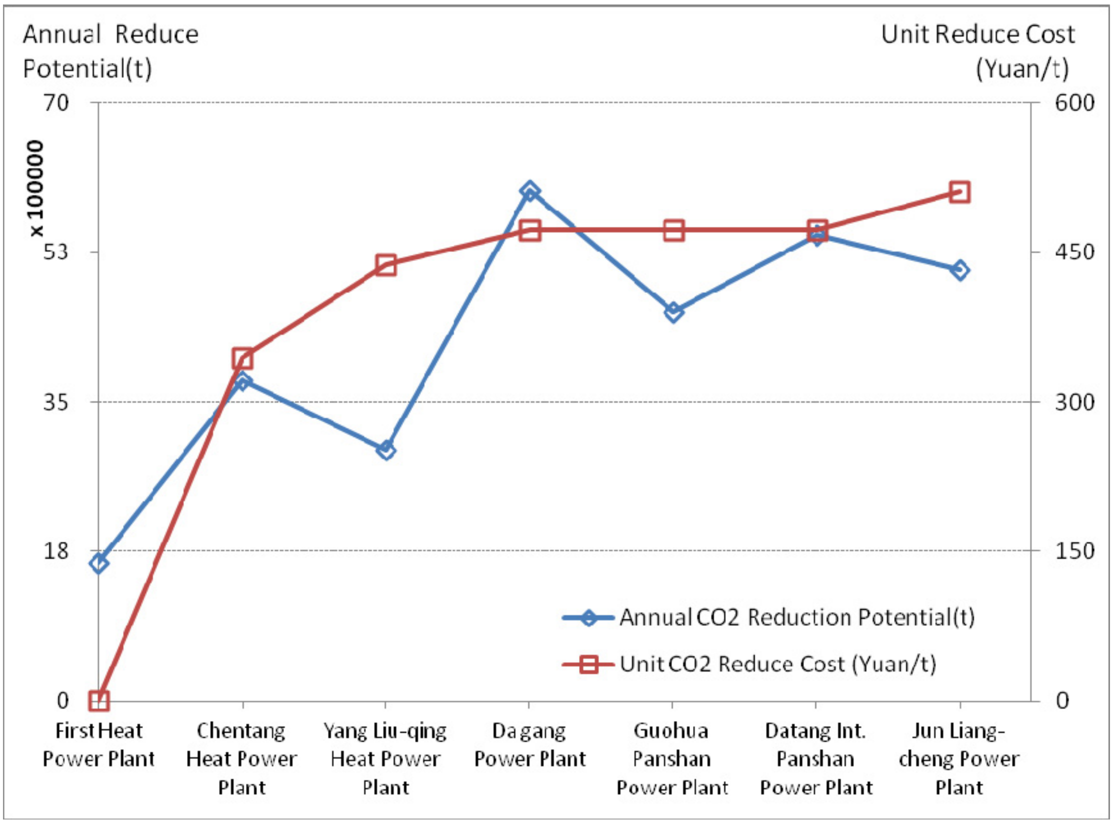

Fig. 12. GHG Scenario optimization results: Annual CO_2 reduction potential curve and unit CO_2 reduce cost curve formed by power plant options.

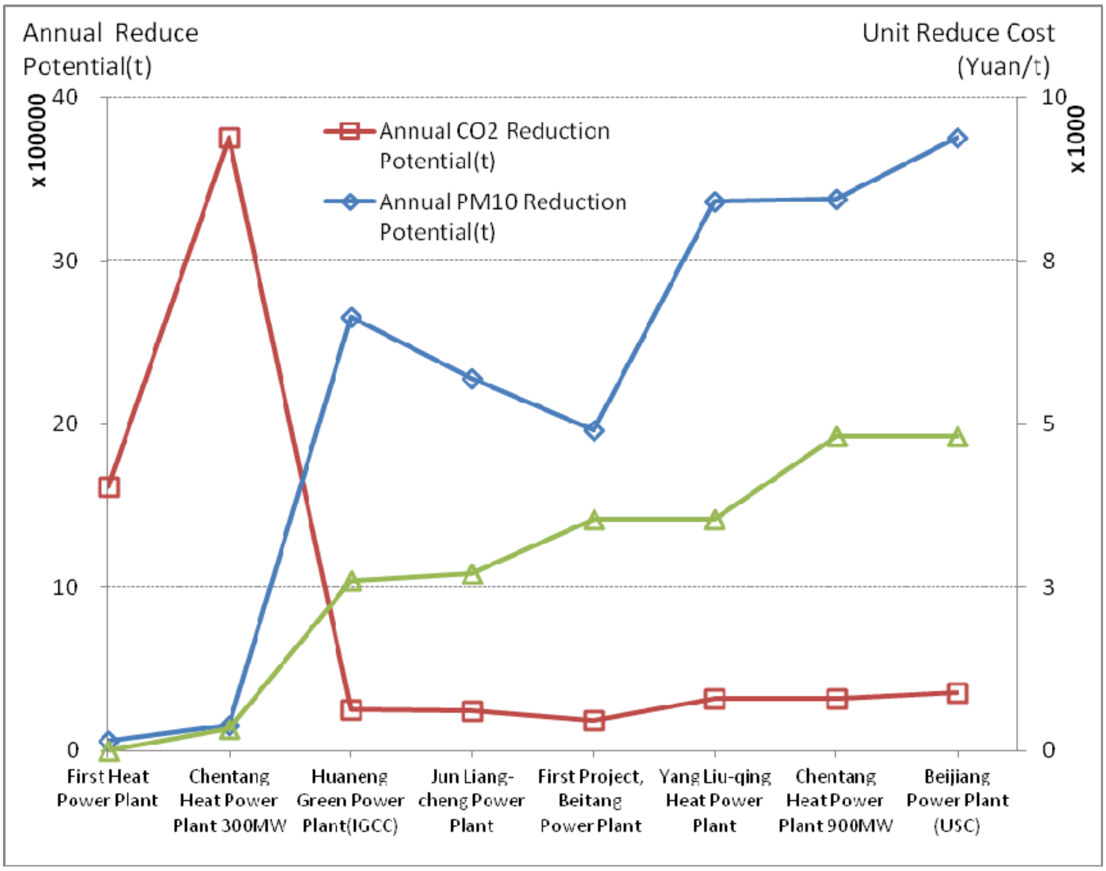

Fig. 13. IES Scenario optimization results: Annual CO_2 reduction potential curve, Annual PM_{10} reduction potential curve and unit CO_2 reduce cost curve formed by power plant options.

the total PM_{10} reduction potential is 12,081.30 t when the total cost is 443.90 Million Yuan from 2010 to 2015, the prospected reduce percentage is 16.15% (See Table 8). The optimized result of LAP scenario shows that: Only utilize PM_{10} reduction end-of -pipe technologies such as retrofit precipitator on existing plants cannot fulfill the new national standard.

In GHG scenario, according to China's GHG emission target is 40%–45% reduction in per unit GDP carbon dioxide emissions in 2020, the emission target of Tianjin was set at an additional 19% reduction of CO_2 emission during the Twelfth Five-Year Plan. As a suggested target scenario (ST) of 19%, the total CO_2 reduction potential is 26,846,886 t when the total cost is 6.45 Billion Yuan from 2010 to 2015, the prospected reduce percentage is 35.1% (See Table 9). The optimized result of GHG scenario shows that: The CO_2 migration potential of GHG scenario can reach the suggested target in Tianjin during the Twelfth Five-Year Plan.

The integrated environmental strategy (IES) scenario aims to meet both air pollutant and CO_2 emission reduction targets which are the same as LAP and GHG scenario. Optimization results regarding the emissions and cost 2010–2015 are presented in Table 10 and Fig. 13. The IES reduction options including: close the 50MW units in First Heat Power Plant Close the 50MW units, retrofit CCS-MEA and bag house precipitator on 300MW units in Chentang Heat Power Plant and build New IGCC 250 MW units. The total PM_{10} reduction potential is 35,930.73 t, the total CO_2 reduction potential is 28,095,386 t when the total cost is 9.69 Billion Yuan in Tianjin from 2010 to 2015. The prospected PM_{10} reduce percentage is 48% and CO_2 reduce percentage is 36.7%. We summarize the comparisons of 4 scenarios in Table 11 and Figs. 14–15, which gives an overview of scenarios preference when creating policies.

The optimized result of IES scenario illustrates that: The PM_{10} and CO_2 migration potential of IES scenario can reach both suggested targets in Tianjin during the Twelfth Five-Year Plan. However, the cost of migration increases 3.24 billion than the GHG scenario, it illustrate that the company and government must concern the unit cost and the total cost to make a wise decision in technologies and reduction measures, the co-benefit options not always the more cost-beneficial choice than separately reduce scenario the under specific target. Cost information should be an important consideration when devising environmental policies. How much emission reduction potential can be achieved will be limited by the costs of bringing about the reduction.

CONCLUSIONS

According to the optimizing analysis, this study indicates that connecting GHG mitigation with current air quality management measures is effective. Promoting Nuclear

Table 8. The Optimization results of LAP scenario.

Coal-fired Power Plant	Unit (MW)	LAP Reduction Scenario	Annual PM_{10} Reduction Potential (t)	Annual Average Technology Cost (Million Yuan)
First Heat Power Plant	50 × 4	Close 50 MW units	162.90	0.00
Chentang Heat Power Plant	50 × 2, 300× 2	Close 50 MW units and retrofit Bag house Precipitator on 300 MW units	389.15	7.70
Jun Liang-cheng Power Plant	100 × 2, 200 × 4	Close 100 MW units and retrofit Electrostatic-bag house Integrated Precipitator on 200 MW units	380.01	22.57
Yang Liu-qing Heat Power Plant	300 × 2	Retrofit Bag house Precipitator on 300 MW units	217.20	7.71
Datang Int. Panshan Power Plant	600 × 2	Retrofit Electrostatic-bag house Integrated Precipitator on 600 MW units	434.40	23.11
Guohua Panshan Power Plant	500 × 2	Retrofit Electrostatic-bag house Integrated Precipitator on 500 MW units	362.00	19.26
Da gang Power Plant	328.5 × 4	Retrofit Bag house Precipitator on 300 MW units	470.60	8.43
Annual Total			2416.26	88.78
2010–2015 Total			12081.30	443.90

Table 9. The Optimization results of GHG scenario.

Coal-fired Power Plant	Unit (MW)	GHG Reduction Scenario	Annual Standard Coal Reduction Potential (t)	Annual CO_2 Reduction Potential (t)	Annual Average Technology Cost (Million Yuan)
First Heat Power Plant	50 × 4	Close 50 MW units	596200.00	1615702.00	0.00
Chentang Heat Power Plant	50 × 2, 300 × 2	Close 50 MW units and retrofit CCS-MEA on 300 MW units	1385120.00	3753675.20	1290.19
Annual Total			1981320.00	5369377.20	1290.19
2010–2015 Total			9906600.00	26846886.00	6450.95

Table 10. The Optimization results of IES scenario.

Coal-fired Power Plant	Unit (MW)	IES Reduction Scenario	Annual PM_{10} Reduction Potential (t)	Annual Standard Coal Reduction Potential (t)	Annual CO_2 Reduction Potential (t)	Annual Average Technology Cost (Million Yuan)
First Heat Power Plant	50 × 4	Close 50 MW units	162.90	596200.00	1615702.00	0.00
Chentang Heat Power Plant	50 × 2, 300 × 2	Close 50 MW units, retrofit CCS-MEA and retrofit Bag house Precipitator on 300 MW units	389.15	1385120.00	3753675.20	1290.19
Huaneng Green Power Plant (IGCC)	250	Build New IGCC units	6634.10	92140.22	249700.00	648.75
Annual Total			7186.15	2073460.22	5619077.20	1938.94
2010–2015 Total			35930.73	10367301.11	28095386.00	9694.70

power plant and other clean energy plants were also effective in air quality improvement and GHG reduction. Integrated strategies were selected by identifying the most cost effective measures through cost-benefit analysis. These integrated environmental strategies made it possible to reduce CO_2.

Through ordering the technologies can find that rebuild Bag-house precipitator in 300 MW units is most cost-benefit in PM_{10} emission reduction in thermal power plant. For CO_2 emission reduction, CCS-MEA is the most effective option for existing plant. The correlation of cost-benefit analysis indicated that the Nuclear Power plant was the most cost effective option to reduce PM_{10} and CO_2 emissions at the

Table 11. Total reduction potential and total abatement cost of four scenarios 2010–2015.

Scenario	PM_{10} Reduction 2010–2015 (t)	CO_2 Reduction 2010–2015 (t)	Coal Saving 2010–2015 (t)	Reduction Cost 2010–2015 (Million Yuan)
BAU	0.00	0.00	0.00	0.00
LAP	12081.30	0.00	0.00	443.94
GHG	0.00	26846886.00	9906600.00	6450.95
IES	35930.73	28095386.00	10367301.11	9694.70

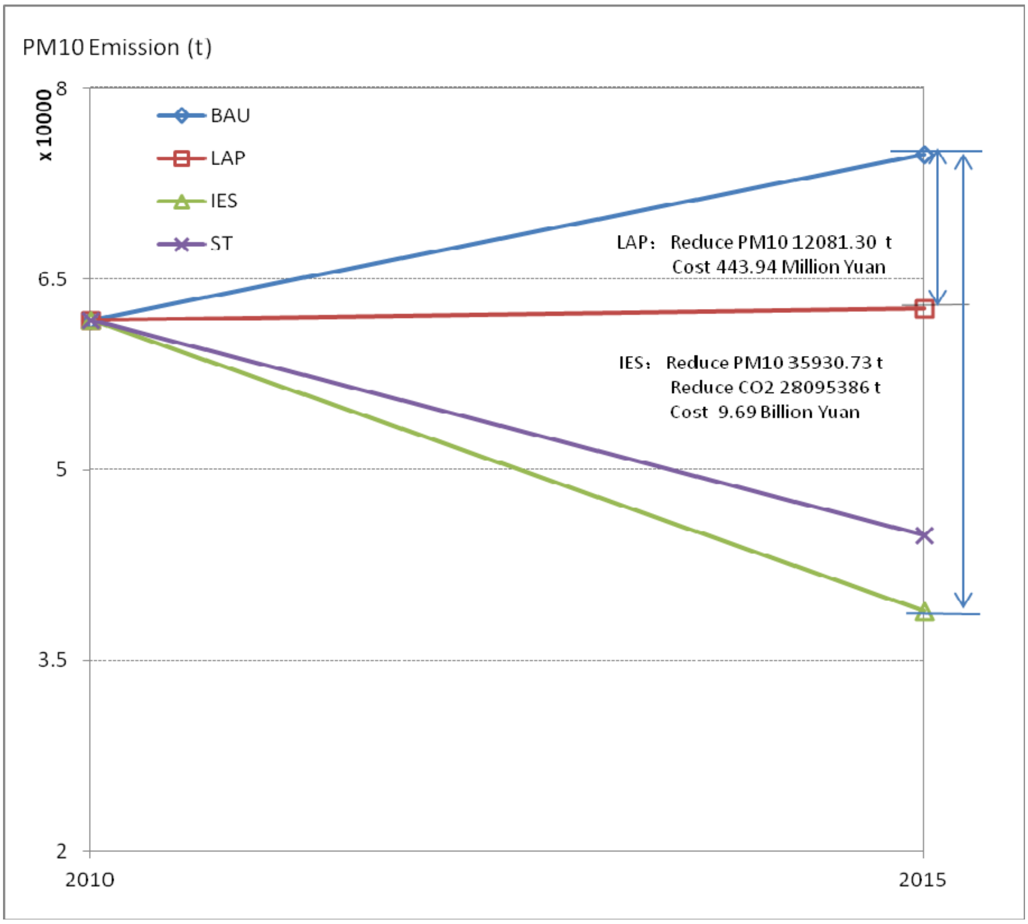

Fig. 14. Comparison of PM_{10} emission and reduce cost in different scenarios from 2010 to 2015.

same time, but IGCC is a safer choice for Tianjin. The integrated environmental strategy (IES) scenario makes it possible to reduce 28,095,386 t of CO_2 and 35,930.73 t of PM_{10} emissions and cost 9.69 Billion Yuan from 2010 to 2015, which beyond both suggested targets of PM_{10} and CO_2 during the Twelfth Five-Year Plan.

This study found that measures to reduce emissions in the coal-fired power industry are particularly effective in reducing air pollutants and CO_2 at the same time. Air pollution reduction benefits as well as associated costs for each measure vary widely.

Through cost-benefit analysis and optimization, the IES scenario was developed to reduce air pollutants and CO_2 at a lower cost than air quality management and GHG measures combined. This study's findings are very important as they address the problem of climate change and air pollution together. Optimized integrated strategies to manage air quality and climate change problems are particularly important for developing countries with limited economic resources and severe air quality problems.

As shown above, there are many win-win and cost-benefit options to reduce PM_{10} and CO_2 emissions. If health benefits, climate change and other environmental benefits were quantified, the effectiveness of the measures would be greater. Additional studies are needed to clarify their effects on emissions and cost effectiveness.

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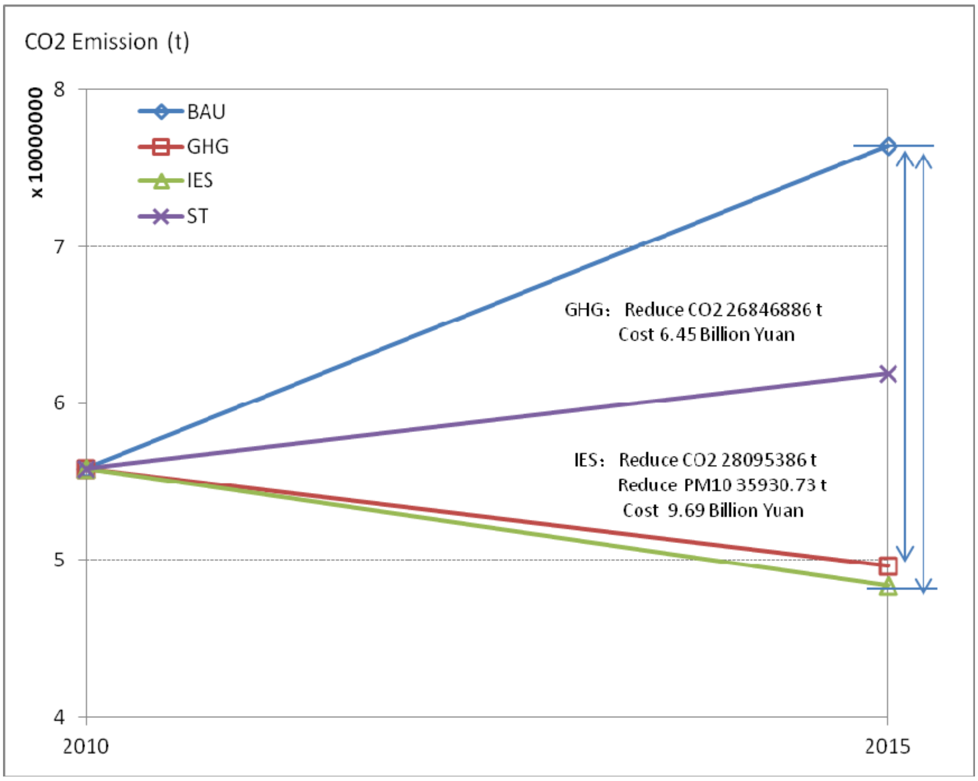

Fig. 15. Comparison of CO_2 emission and reduce cost in different scenarios from 2010 to 2015.

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