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# Integrating mitigation of air pollutants and greenhouse gases in Chinese cities: development of GAINS-City model for Beijing

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A B S T R A C T

Strong economic growth in China has fueled development of cities where increase in energy demand and transportation lead to severe air pollution. The cities contribute also a significant share of the national greenhouse gas emissions. We identify strong synergies between air quality and climate relevant measures that would allow improving cost-efficiency of air pollution policies. In order to help local policy makers to identify viable and efficient solutions, we developed a city-scale emission model (GAINS-City) based on the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model developed by the International Institute for Applied Systems Analysis (IIASA, Austria). The GAINS-City model relies on a technology-based approach to evaluate the co-benefits of various policies. This approach allows for estimation of emission reductions of several pollutants (including $SO_2$, $NO_X$, PM) and $CO_2$ for individual policies and support evaluation of co-benefits. In addition, a reduction index, an integrated rank of the individual reductions potential, was defined to recommend the priority of policies implementation. The approach will have great potential to be applied in many large cities with local input data and/or minor structure modifications. We conducted a case study in Beijing to demonstrate the model features. Based on the technology-based evaluation approach, policy packages were designed and implemented in policy scenarios. The emissions under three scenarios (*Baseline*, *Air Quality*, and *Strict Air Quality*) in base year (2005) and future years (2020 and 2030) were estimated. The results indicate a significant reduction potential. In 2030, implementation of *Air Quality* and *Strict Air Quality* scenarios could result in reductions of 39–48% of $SO_2$ emissions, 38–42% of $NO_X$ emissions, 37–55% of $PM_{2.5}$ emissions and 5–22% of $CO_2$ emissions respectively, compared with the Baseline scenario. The results demonstrated air quality policies and measures could also have co-benefits of reducing $CO_2$ emissions. However, there is no significant difference of reductions between the two policy scenarios, which indicates the limited further reduction potential in the stricter air quality case. This calls for a wider application of cleaner technologies, such as IGCC and CCS, and more aggressive air quality measures by neighboring provinces to control regional air pollution.



## 1. Introduction

As the primary energy consumers and pollutants emitters, cities have the potential to play the role as "engines of environmental policy" (Granberg and Elander, 2007) and the best implementer of co-control. Co-benefits of the simultaneous abatement of GHGs and air pollutants have recently called the attention. The additional environmental benefits from carbon intensity reduction measures have been widely researched (Asbjørn Aaheim and Seip, 1999; Cifuentes et al., 2001; Wang and Smith, 1999). The research results showed the good prospects of co-control.

Emission abatements from Chinese megacities attracted worldwide attention, as China became the largest $CO_2$ emitter and an

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important contributor to the global air pollution budget, e.g., 28% of anthropogenic $SO_2$ emissions (Smith et al., 2011) and 10% of black carbon emissions from combustion (Bond et al., 2007). Due to the higher energy consumption intensity (Dhakal, 2009) in urban areas, Chinese local governments are taking active actions in searching for win–win solutions and they accepted strict energy-saving task to fulfill China's promise of reducing carbon intensity by 40–45% by 2020 (State Council Office Announcement, 2009). Besides, they are required to implement the World Health Organization (WHO) recommended interim target of an annual average of 35 $\mu g/m^3$ for particles with diameters less than or equal to 2.5 $\mu m$ ($PM_{2.5}$) by the end of 2015. Although meeting the standard is a great challenge owing to the coal-based energy structure, the willingness and enthusiasm of government has never been so strong pushed by the public (Zhang et al., 2012). Consequently, guidance for policy development and evaluation is urgently needed.

There have been several attempts to consider scientific advice in the process of development of local air quality strategies where elements of climate change policy would be integrated. However, the previous studies provided a rather general evaluation of policy package at a sector level (Chen et al., 2006; Kennedy et al., 2010, 2009), which ignored the individual reduction potential of policy and lacked detailed information to guide policy-by-policy decisions. Some studies sought to assess co-benefits of specific measures (Aunan et al., 2004; Mestl et al., 2005) but the policy they analyzed had obvious regional characteristics, such as cleaner production projects of coke industry in Taiyuan City, and did not cover significant emission sources comprehensively, such as transportation sectors. As a result, we have developed a detailed technology-based evaluation approach to assess the benefits for each individual policy. The policy scenarios designed under this approach are based on policy-by-policy analysis of emission reduction potential. This approach is a major update of current GAINS model, where the benefits were based on sector-level analysis.

The integrated assessment model GAINS have been successfully used in evaluating co-benefits and have been applied to guide the key negotiation on air pollution control agreements in Europe during last two decades (Schöpp et al., 1998; Amann et al., 2011). It supported the discussion of the national emission ceilings for the 1994 Second Sulfur Protocol (Tuinstra et al., 1999), the 1999 Gothenburg multi-pollutant Protocol (Hordijk and Amann, 2007) and its recent revision. In addition, the technology-based estimation methodology and numerous source categories embedded in the GAINS model provided the possibility of detail policy-level evaluation. So far, the GAINS model has focused on large (regional, national) scale application while the city-scale emission calculation and policy assessment requires some additional development, i.e., adding specific source categories, technologies and control options to improve characterization of local conditions in the model. Compared with extant co-benefit models applied in Asia, e.g., MARKAL optimization model for Shanghai (Gielen and Changhong, 2001) and AIM/local model (AIM Project Team, 2002), GAINS-City model has a more complete representation of source categories and included pollutants, consequently a more realistic characterization of measures to guide policy decisions.

This paper describes the methodology of the new city-scale emission model (GAINS-City), especially the technology-based approach to evaluate co-benefits at policy level. A policy list based on a careful review of the existing and potential climate-friendly air quality policies in China was integrated in GAINS-City. Several examples of power plants, industrial combustion, domestic sector, industrial process and transportation sector were presented to show the principle of model simulation for individual policy. In addition, a case study of Beijing was conducted to demonstrate the model features.

## 2. Methodology

### 2.1. Key concept of the GAINS-City model

GAINS-City model builds on the experience of the regional GAINS model application. It inherits its model structure and functions, but emphasizes the evaluation of co-benefits on GHGs and air pollutants of climate-friendly air quality management policies in urban areas. The GAINS model developed by the International Institute for Applied Systems Analysis (IIASA) in Laxenburg, Austria, has demonstrated its capacity to evaluate the co-benefits of environmental policies at global and national scale (Amann et al., 2008; Shindell et al., 2012). By estimating emissions, reduction potentials and costs for six air pollutants ($SO_2$, $NO_X$, $PM_{2.5}$, $PM_{2.5-10}$, $NH_3$, VOC) and for six greenhouse gases ($CO_2$, $CH_4$, $N_2O$, HFCs, PFCs, $SF_6$) included in the Kyoto protocol, GAINS model supports governments to explore the mitigation strategies that achieve air quality and greenhouse gas abatement targets simultaneously at least cost (Amann et al., 2011).

In order to evaluate the co-benefits of control measures at city level, we proposed two major adjustments. We expanded the source categories of original GAINS model, and update the emission factor database according to China's local measurements. For example, we divided the cement kilns into vertical kilns, precalciner kilns and other rotary kilns; and coke ovens into traditional ovens and model ovens. These improvements would make the GAINS-City model more suitable for city-scale emission estimation and co-benefits assessment.

### 2.2. Technology-based policy evaluation approach

The GAINS model adopted technology-based methodology to estimate current and future emissions following Eq. (1).

$$E_p = \sum_k \sum_m A_k ef_{k,m,p} x_{k,m,p} \tag{1}$$

where, $k$, $m$, $p$ represents activity type, abatement measure, pollutant respectively, $E_p$ stands for emission of pollutant $p$, $A_k$ stands for activity data of type $k$, $ef_{k,m,p}$ stands for emission factor of pollutant $p$ for activity $k$ after application of control measure $m$ (where $m$ includes also the no control situation), $x_{k,m,p}$ stands for penetration of control measure $m$ for pollutant $p$ of activity $k$. By simulating the modification of activity data and technology penetration induced by a specific policy and policy package, the GAINS-City model can assess the further reduction potential. Introduction of some policies is straightforward, especially the impact of technology renewal on technology penetration. For example, the policy "installation of SCR in 80% of newly-built coal-fired power plants" can be directly converted into the penetration rate of SCR in the GAINS-City model and reduces $NO_X$ emissions. However, some simulation needs to involve various parameters and consider potential feedbacks on the energy balance. We picked up some "indirect" policies to represent our technology-based methodology to evaluate the co-benefits of local climate-friendly air quality management policies.

#### 2.2.1. Substitution of natural gas consumption for coal consumption

Natural gas is encouraged as substitute for coal in the power plant sector and final demand sectors in urban areas, owing to its higher energy efficiency and lower emission rates during combustion processes. The amount of $CO_2$, $NO_X$, and $SO_2$ emitted from natural gas-fired power plants are only 50%, below 30%, and 1% of those from coal-fired power plants for per unit of electricity generated (U.S.EPA, 2002). We quantified the emission reduction from replacing coal by natural gas, assuming the same energy service. The emission reduction of such fuel switch process was calculated by Eq. (2).

$$\Delta E = \Delta A_{Bef} ef_{Bef,m,p} x_{Bef,m,p} - \left( \Delta A_{Bef} eff_{Bef} / eff_{Post} \right) ef_{Post,m,p} x_{Post,m,p} \tag{2}$$

where, *Bef*, *Post*, *m*, *p* represents baseline (before-policy) activity type (coal in this example), post-policy activity type (natural gas in this example), abatement measure, and pollutant respectively; $\Delta E$ stands for the emission reduction; $\Delta A_{Bef}$ stands for the change in activity data caused by target policy; $ef_{Bef,m,p}$ and $ef_{Post,m,p}$ stand for emission factor of pollutant $p$ for activity Bef and Post after application of control measure $m$; $x_{Bef,m,p}$ and $x_{Post,m,p}$ stand for penetration rate of control measure $m$ for pollutant $p$ of activity *Bef* and *Post; eff*$_{Bef,m,p}$ and eff$_{Post,m,p}$ stand for the energy efficiency of activity Bef and Post during energy consumption process. The $\Delta A_{Bef}$ represents the activity difference inferred from the reference (*Bef*) and policy (*Post*) activity data; see also Eq. (3). For example, in the policy case "Substitution of natural gas-fired industrial boilers for 70% of coal-fired ones in 2020", the $\Delta A_{Bef}$ reflects lower coal consumption of industrial boilers in 2020, i.e., reduced by 30%. Such method was not only applied for fuel switch process, but also for source category switch process. For example, the policy "Phasing out of coal-fired power plants with small capacity" is equal to moving coal consumption from existing small plants to newly built large plants.

### 2.2.2. Switch from heat only boilers to combined heat and power (CHP) schemes in industry and district heating systems

In this scenario the effects of cogeneration of electricity and heat (CHP) are analysed. Heat supplied from CHP plants replaces stem and hot water generated in traditional coal boilers. This results in fuel savings and consequently also reduces the emissions of air pollutants. The scenario defines heat demand in a given city $\Delta H$ that is to be met by the CHP scheme in addition to the base case situation. This is associated with production of electricity $\Delta EL$ in CHP plants. Difference in fuel (coal) consumption includes: (i) fuel needed by the CHP plants, (ii) fuel saved through phasing-out heat only boilers, and (iii) fuel saved in conventional power plants to produce electricity supplied by CHP scheme. It can be calculated by Eq. (3):

$$\Delta A_{Bef} = (\Delta H + \Delta EL)/\eta_{CHP} - \Delta H/\eta_{BO} - \Delta EL/\eta_{PP} \tag{3}$$

where, $\Delta A_{\mathrm{Bef}}$ represents change in fuel (coal) demand compared with the base case situation; $\Delta H$ represents heat demand to be met by CHP plants in addition to the base case situation; $\Delta EL$ represents electricity produced in CHP schemes; $\eta_{\mathrm{CHP}}$, $\eta_{\mathrm{BO}}$, $\eta_{\mathrm{PP}}$ stands for the efficiency of the CHP plant, the heat only coal fired boiler and the CHP plant respectively.

### 2.2.3. Phasing out of cement plants with vertical kilns and non-precalciner rotary kilns

Cement sector was subdivided in the GAINS-City model into vertical kilns, precalciner kilns and other rotary kilns according to the present status of cement production in China. In addition, the emission factors of corresponding cement kilns were updated in GAINS based on a recent study (Lei et al., 2011). Such modification contributed to the improvement of estimation accuracy for cement emissions, owing to the great variations of emission factors for different cement kilns. In addition, the detailed classification of source category provided the possibility to estimate the emission reduction of rapid technology shift forced by policy. For example, under this policy, the cement production from vertical kilns and non-precalciner rotary kilns would be transferred to precalciner kilns that are much cleaner. Although not discussed here in detail, a similar procedure was applied for coke sector where two categories where distinguished: traditional coke ovens and modern coke ovens allowing simulation of technology shift in this sector.

### 2.2.4. China V standard for light duty gasoline vehicles

We constructed a simplified vehicle fleet model to support the simulation of implicating new emission standard for vehicles. In our model, the introduction of new emission standard results in reallocation of fuel between vehicles complying with different emission limits, currently assuming that the fuel economy is independent on vehicle emission standard. In the example discussed here, the fuel used in the additional stock of China IV vehicles would be allocated to China V vehicles from 2015 onwards. The baseline fuel consumption by vehicle categories and control technology distribution originates from the GAINS model and is given for every five years. We assume the average annual rate of change within each five year period to derive specific year technology penetration, i.e., the China V penetration after transformation is presented by Eqs. (4) and (5).

$$X_{IV,i,Star} = X_{IV,i\ \ 1,End} + \left(X_{IV,i,End}\ \ \ X_{IV,i\ \ 1,End}\right)/5 \times Start \tag{4}$$

$$X_{V,j,End} = \left(A_j \times X_{IV,j,End} - A_i \times X_{IV,i,Start}\right) \Big/ A_j \tag{5}$$

where, IV, V stands for the stage of China IV and V standards; the sequence of every five-year period is numbered, ranging for 1 to 6 during 2005–2030, and *i*, *j* stands for the number of the period including policy implementation year and the number of the projected period; the sequence of year in the five-year period is numbered as well, ranging from 1 to 5, and *End* and *Start* stands for the number of the last year of the five-year period and the policy implementation year. For example, if we projected the China V penetration in 2025, $i = 3$, $j = 5$, $End = 5$ and $Start = 5$. In addition, the life spans of the newly-promoted "cleaner" vehicles were taken into consideration. Based on the mandatory standards for vehicle scrappage (Ministry of Commerce of China, 2006) and previous work (Huo et al., 2012), vehicles were required to be scrapped when they reached a given age (e.g., 15 years for light duty vehicles) in our model. And the scrappage standard was assumed to be carried out strictly without considering the survival rates, as we tried to explore the maximum reduction potential of the fleet technology renewal process.

## 2.3. Policy embedded in model

Based on a careful review of air-quality related laws and regulations, a series of policies were summarized to be simulated in the GAINS-City model (Table 1). Based on the extensive literature review of existing emission inventories at city level e.g., (Aunan et al., 2004; Chen et al., 2006; Kennedy et al., 2010, 2009; Mestl et al., 2005), we identified the source categories who may have significant contribution to cities. The policy packages were then especially designed for those source categories. In addition, since this model is target to evaluate emission reduction potential for near and middle term (10–20 years), we only use current available abatement technologies to construct our policy package. By a careful study on 12th Five-Year Plan for National Economic and Social Development, Regional Air Quality Management (RAQM) Guidance and Beijing Municipal Clean Air Action Plan, We picked up all the policies related to the extant emission source in the GAINS-City and integrated them into the model. For the large emission sources, e.g., power plants, extra stronger policies were introduced, e.g., IGCC.

**Table 1**
List of policy embedded in GAINS-City model by sector.

| Sector | ID | Content |
|---|---|---|
| Power plants | P1 | Growth of the usage of electricity generated from power plants outside city boundary |
| | P2 | Phasing out of coal-fired power plants with small capacity |
| | P3 | Substitution of natural gas-fired power plants for coal-fired ones |
| | P4 | Substitution of IGCC for traditional coal-fired power plants |
| | P5 | Substitution of natural gas-fired heating plants for coal-fired ones |
| | P6 | Installation of CCS |
| | P7 | Promotion for low-sulfur coal in power plants |
| | P8 | Installation of FGD in coal-fired power plants |
| | P9 | Installation of FF in newly-built coal-fired power plants |
| | P10 | Installation of ESP + FF in newly-built coal-fired power plants |
| | P11 | Installation of FF in old coal-fired power plants |
| | P12 | Installation of LNB in power plants |
| | P13 | Installation of SCR in newly-built coal-fired power plants |
| | P14 | Installation of SCR in old coal-fired power plants |
| Industrial combustion | I1 | Improvement of energy efficiency in industrial combustion sector |
| | I2 | Substitution of CHP for traditional coal-fired industrial boilers |
| | I3 | Phasing out of coal-fired industrial boilers with small capacity |
| | I4 | Substitution of natural gas-fired industrial boilers for coal-fired ones |
| | I5 | Promotion for low-sulfur coal in industrial combustion sector |
| | I6 | Installation of FGD in coal-fired industrial boilers |
| | I7 | Installation of FF in newly-built coal-fired industrial boilers |
| | I8 | Installation of LNB in industrial boilers |
| | I9 | Installation of wet scrubbers in old industrial boilers |
| | I10 | Installation of FF in old coal-fired industrial boilers |
| Domestic sector | D1 | Improvement of energy efficiency in domestic sector |
| | D2 | Substitution of district heating for decentralized heat-supply |
| | D3 | Phasing out of residential coal stove |
| | D4 | Growth of natural gas consumption in domestic sector |
| | D5 | Promotion for low-sulfur coal in domestic sector |
| | D6 | Installation of wet scrubbers in residential coal-fired boilers |
| | D7 | Installation of LNB in residential natural gas-fired boilers |
| Industrial process | IP1 | Phasing out of cement plants with vertical kilns and non-precalciner rotary kilns |
| | IP2 | Phasing out of coke plants with old ovens |
| | IP3 | Ban of newly built/renovated/expanded cement plants |
| | IP4 | Ban of newly built/renovated/expanded lime plants |
| | IP5 | Ban of newly built/renovated/expanded brick plants |
| | IP6 | Ban of newly built/renovated/expanded glass plants |
| | IP7 | Ban of newly built/renovated/expanded iron and steel plants |
| | IP8 | Ban of newly built/renovated/expanded coke plants |
| | IP9 | Phasing out of cement plants |
| | IP10 | Phasing out of lime plants |
| | IP11 | Phasing out of brick plants |
| | IP12 | Phasing out of glass plants |
| | IP13 | Phasing out of sinter plants |
| | IP14 | Phasing out of coke plants |
| | IP15 | Substitution of industrial natural gas-fired kilns for coal-fired ones |
| | IP16 | Installation of FF in cement plants |
| | IP17 | Installation of SNCR in precalciner kilns of cement plants |
| | IP18 | Installation of FF in lime plants |
| | IP19 | Installation of end-of-pipe PM control in sinter plants |
| | IP20 | Stricter control for fugitive sinter plants |
| | IP21 | Installation of end-of-pipe $SO_2$ control in sinter plants |
| Transportation | T1 | China IV standard for light duty vehicles |
| | T2 | China IV standard for heavy duty diesel vehicles |
| | T3 | China V standard for heavy duty diesel vehicles |
| | T4 | China III standard for motorbike |
| | T5 | China II standard for non-road vehicles |
| | T6 | China IV standard for gas vehicles |
| | T7 | China V standard for light duty gasoline vehicles |
| | T8 | China VI standard for light duty gasoline vehicles |
| | T9 | China VI standard for heavy duty diesel vehicles |
| | T10 | China III standard for non-road vehicles |
| | T11 | China IV standard for non-road vehicles |
| | T12 | China V standard for non-road vehicles |
| | T13 | China VI standard for non-road vehicles |
| | T14 | Scrappage of pre-China I gasoline vehicles |
| | T15 | Scrappage of pre-China I diesel vehicles |
| | T16 | Scrappage of China I gasoline vehicles |
| | T17 | Scrappage of China I diesel vehicles |
| | T18 | Scrappage of China II gasoline vehicles |
| | T19 | Scrappage of China II diesel vehicles |
| | T20 | Limitation of the volume of private cars |
| | T21 | Substitution of gas vehicles for traditional ones |
| | T22 | Substitution of alternative energy public bus for traditional one |
| | T23 | Substitution of alternative energy taxi for traditional one |
| | T24 | Substitution of alternative energy private car for traditional one |
| | T25 | Installation of SCR in diesel vehicles |

The policies were proposed from two aspects: energy structure adjustment and end-of-pipe control technology update. The former aspect referred to the direct energy saving targets in final consumer sectors, fuel type switch, ban of newly built high-pollution projects and elimination of backward production capacity. Such as promotion for gas industrial boilers, ban of newly built/renovated/expanded cement plants in urban areas. The latter aspect included existing mature technology, such as selective catalytic reduction (SCR) and fabric filter (FF), and some potential technology, such as carbon capture and storage (CCS).

The policies were simulated separately or jointly as described in Section 2.2 to achieve the emission reduction of single policy or policy package. When we had the emissions under baseline scenario, we could define a reduction index to rank the priority of policy based on the emission reduction achieved in the last step by Eq. (6).

$$index = \sum_i \Delta E_i / E_i \tag{6}$$

where $i$ stands for species, including all the estimated GHGs and air pollutants; $\Delta E$ presents the emission reduction and $E$ presents the total emission under baseline scenario. The rank is meaningful for picking up high-efficiency policy and searching for win–win solutions.

## 3. Case study

### 3.1. Brief introduction of Beijing

Beijing, China's capital, is one of the world's largest megacities with a population of more than 19.6 million and a vehicle fleet of more than 4.8 million in 2010 (Beijing Statistical Bureau, 2011). The large population and rapid economic growth have resulted in large amount of energy consumption, over 69 million tce in 2010, of which coal accounted for 26% (Beijing Statistical Bureau, 2011). The rising energy consumption without effective air pollution control measures deteriorated the urban air quality. Previous studies showed that average daily concentrations of $PM_{2.5}$ ranged from 91 to 169 μg/m$^3$ between 2000 and 2005, much higher than US National Ambient Air Quality Standards (65 μg/m$^3$) (Chan et al., 2005; Hao and Wang, 2005; He et al., 2001; Streets et al., 2007; Zheng et al., 2005). Besides, the official report showed that 22% of days exceeded the previous Grade II Ambient Air Quality Standard (State Environmental Protection Administration of China, 1996) in 2010 (Beijing Statistical Bureau, 2011), which was far beyond the WHO recommended standard.

Beijing local government has taken actions to improve air quality since 1970s. Especially after 1998, a series of strong control measures were carried out in stages (11 stages in total) to reach the air-quality target of 2008 Beijing Olympic Games (Chai et al., 2006). Recently, aiming at meeting the new Ambient Air Quality Standard (Ministry of Environmental Protection, 2012), more control measures will be expected. Meanwhile, the government is trying to integrate $CO_2$ reduction into extant air pollution control policy framework. As a result, the past and future co-benefits of each measure need to be carefully assessed.

### 3.2. Baseline emissions

The baseline emissions of Beijing during 2005–2030 were estimated by Eq. (1). The detailed energy use, industrial production and vehicle activity data of base year were primarily based on Beijing Statistical Yearbook (Beijing Statistical Bureau, 2006 and 2011) and the technology penetration rates follow GAINS assumptions. The baseline emission projection draws on the socio-

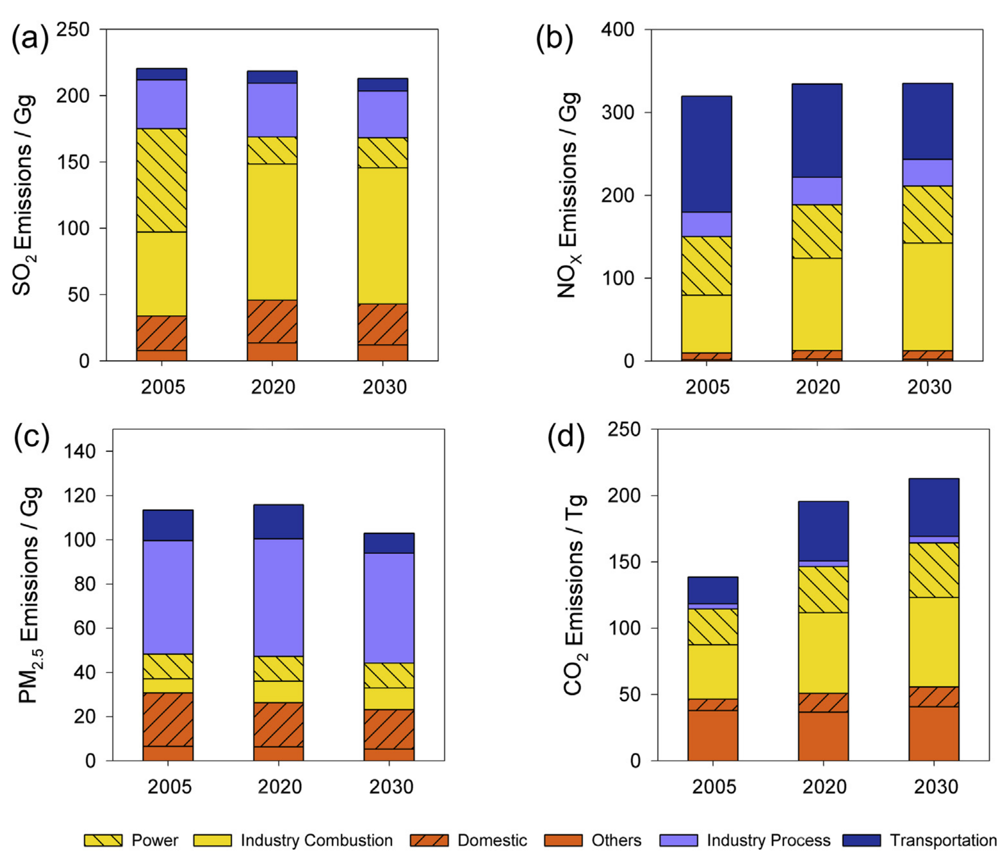


**Fig. 1.** Emission of $SO_2$, $NO_X$, $PM_{2.5}$ and $CO_2$ in 2005, 2020, 2030 under baseline scenario.

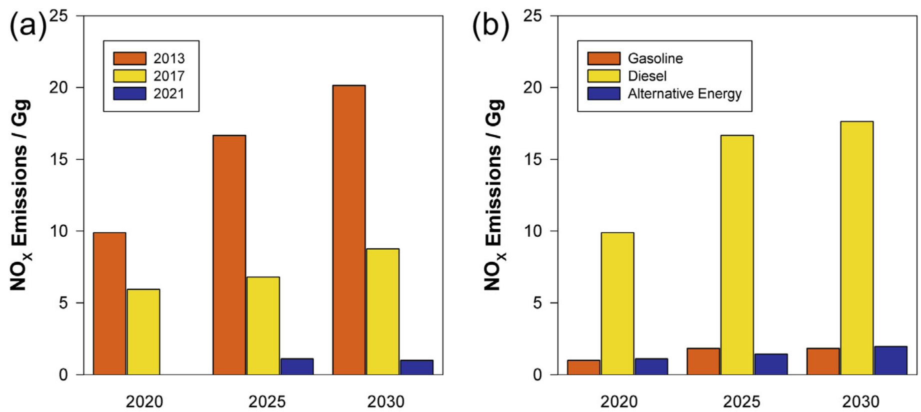


**Fig. 2.** Emission reductions of $NO_X$ by vehicle related policies: (a) Implementation of China VI standard for heavy duty diesel vehicles in 2013, 2017 and 2021; (b) Gasoline: Implementation of China VI standard for light duty gasoline vehicles in 2020; diesel: Implementation of China VI standard for heavy duty diesel vehicles in 2015; alternative energy: Promotion for alternative energy vehicles (40% of public bus and taxi and 10% of private cars in 2030).

economic and energy use projections of the Chinese Energy Research Institute. Implementation rates of emission control measures used in the model follow the assumption that policies and regulations on air pollution control measures before 2010 were fully implemented as foreseen, and that no additional measures were adopted. More detailed information could be downloaded from the GAINS-City model website (GAINS, 2011).

Fig. 1 presents the emissions of Baseline scenario by sector. In 2005, the total emissions of $SO_2$, $NO_X$, $PM_{2.5}$ and $CO_2$ in Beijing were 220.4 Gg, 319.5 Gg, 113.5 Gg, and 138.6 Tg, respectively. Power plants were the largest source of $SO_2$ emissions, accounting for 35% of total emissions. Transportation contributed 44% of $NO_X$ emissions, followed by power plants (22%) and industry combustion (21%). Industrial processes (45%), especially cement production (22%) dominated the $PM_{2.5}$ emissions. The largest source of $CO_2$ emissions was industrial combustion, accounting for 30% of total emissions.

$CO_2$ emissions would increase sharply afterward due to the rapid growth of energy demand and lack of effective energy structure adjustment under Baseline scenario. In 2030, the $CO_2$ emissions would nearly double compared to 2005. The control policies, especially the installation of various end-of-pipe measures, have a potential to offset the projected increase in emissions of air pollutants. The $SO_2$, $NO_X$, and $PM_{2.5}$ emissions could be stabilized at the level of 2005.

### 3.3. Policy-level simulation results analysis

The technology-based policy evaluation approach provides the possibility to assess the policy-by-policy co-benefit and supports choice of most efficient single policies to develop a comprehensive policy packages. Sensitivity analysis is important for such policy making process and helps understanding the reasons for

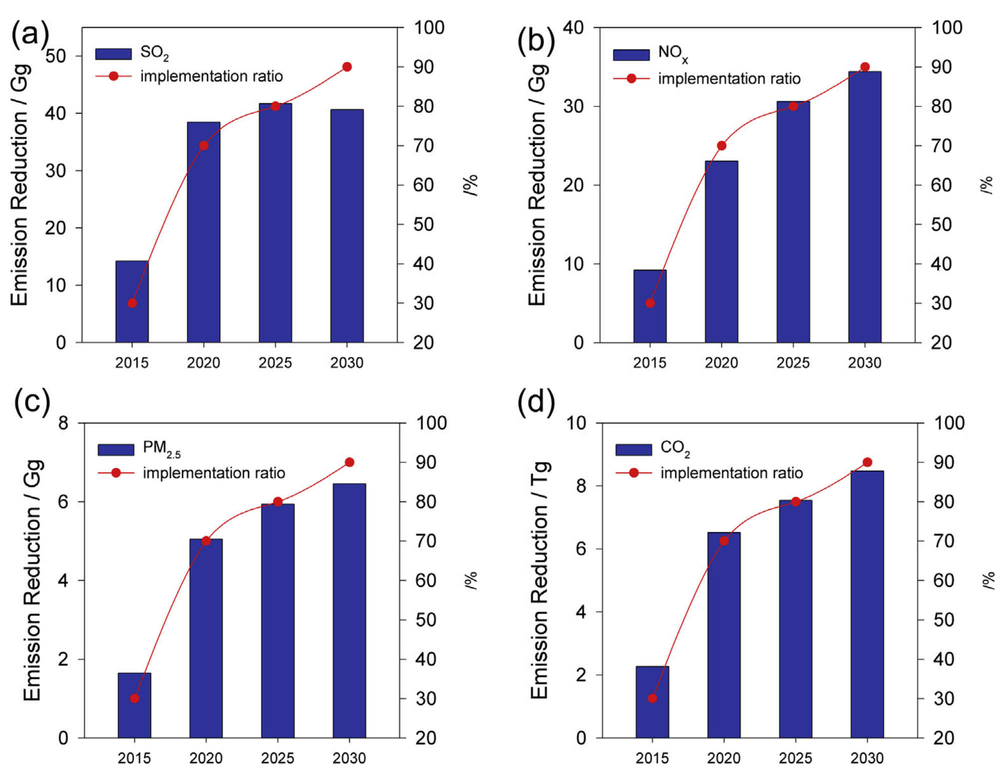


**Fig. 3.** Emission reductions of $SO_2$, $NO_X$, $PM_{2.5}$ and $CO_2$ by natural gas-fired industrial boilers.

discrepancy in emissions among different policy implementation processes, policy packages, and target species.

The policy implementation process, including execution time and stringency, is a significant factor affecting final emissions. Fig. 2a illustrates the emission reductions of the policy "implementation of China VI control for heavy duty diesel vehicles in 2013, 2017 and 2021". Generally, the reductions decreased with the delay of implementation year, but the reduction rates varied with time, due to the changes in activity data over time. Owing to the decline of fuel consumption in heavy duty vehicles during 2020–2030 assumed in the baseline scenario, the additional stocks with stricter emission standard would be limited and introduction of China VI standard after 2020 (2021 in this case) made only little impact. However, advancing implementation of this policy by four years (2013 vs. 2017) was estimated to increase reductions by a factor 2.3 in 2030. The simulation results indicate the urgent necessity of early implementation of new vehicle emission standard.

The priority of policy is another important factor worth consideration. Fig. 2b compares the reduction potential of policy for light duty gasoline vehicles, heavy duty diesel vehicles, and alternative energy vehicles. In 2030, implication of China VI standard for heavy duty diesel vehicles in 2015 would contribute over 9 times higher reductions than the combined policy of China VI standard for light duty gasoline vehicles in 2020 and alternative energy vehicles (10% of private cars and 40% of public buses and taxi in 2030). As a result, "the heavy duty diesel vehicles policy" should receive most attention and its strict implementation is of high priority.

Each of the discussed policies will affect emission of several pollutants. This is taken into account in the comprehensive evaluation of a specific policy. Fig. 3 shows the emission reductions of $SO_2$, $NO_X$, $PM_{2.5}$ and $CO_2$ along with the increasing rates of substitution of natural gas-fired industrial boilers for coal-fired boilers. In 2030, such policy affecting 90% of coal-fired boilers would result in reductions of 41 Gg $SO_2$, 34 Gg $NO_X$, 6 Gg $PM_{2.5}$, and 8 Tg $CO_2$, respectively. The energy related measures, such as fuel switch and energy efficiency improvement, are always win–win solutions for GHGs and air pollutants abatement.

We ranked the policies presented in Table 1 by the reduction index defined by Eq. (6) and selected the top 15 policies (Table 2).

**Table 3**
Major assumptions of the policy scenarios.

| ID | Baseline | AQ | SAQ |
|---|---|---|---|
| I4 | | ✓ | ✓ |
| D1 | | | ✓ |
| IP3 + IP9 | | ✓ | ✓ |
| IP16 | | | ✓ |
| IP13 | | ✓ | ✓ |
| D4 | | ✓ | ✓ |
| P1 | | | ✓ |
| P13 + P14 | | ✓ | ✓ |
| D2 | | ✓ | ✓ |
| I1 | | | ✓ |
| T9 | | ✓ | ✓ |
| P9 | | | ✓ |
| P12 | | ✓ | ✓ |
| T21 + T22 + T23 + T24 | | | ✓ |
| T7 + T8 | | ✓ | ✓ |

The combination of policies in Table 2 would make contributions to taking advantage of the co-benefits and achieving air quality and carbon mitigation targets, resulting also in lower implementation costs (see for example (Amann et al., 2008)). The ranking is as expected to change for different time horizon, for example, we expect that options like introduction of CCS would appear later. CCS does not belong to the top 15 policies listed in Table 2 since its maximum projected penetration by 2030 was estimated at 10%, but its rank would increase with time.

### 3.4. Emission projections under policy scenarios

We designed two scenarios based on the co-benefits assessment of control measures in Section 2.3 to explore the reduction potential of Beijing: air quality (AQ) scenario and strict air quality (SAQ) scenario. The scenarios draw on the set of top 15 measures (Table 2) selected as described in Section 3.3. AQ scenario emphasizes the recently published (after 2010) policy and illustrates the reduction resulting from strict implementation of existing measures. We believe that efficient implementation of most recent policies as depicted in the AQ scenario could stimulate further progress in

**Table 2**
List of efficient policy and their emission reduction in 2030.

| Rank | ID | Remark | Index | Emission reduction in 2030, Gg (Tg for $CO_2$) | | | |
|---|---|---|---|---|---|---|---|
| | | | | $SO_2$ | $NO_X$ | $PM_{2.5}$ | $CO_2$ |
| 1 | I4 | Proportion of coal-fired boiler replaced by natural gas-fired boiler in fuel consumption: 70% in 2020 and 90% in 2030 | 0.39 | 40.67 | 34.40 | 5.77 | 8.47 |
| 2 | D1 | Increasing rate of energy efficiency: 10% in 2020 and 20% in 2030 | 0.25 | 9.58 | 26.33 | 4.96 | 16.55 |
| 3 | IP3 + IP9 | Policy implication year: 2013 for IP3; Proportion of closed plants in production: 40% in 2020 and 60% in 2030 for IP9 | 0.23 | 4.88 | 12.82 | 15.77 | 3.66 |
| 4 | IP16 | Policy implication year: 2015 | 0.23 | 0.00 | 0.00 | 23.38 | 0.00 |
| 5 | IP13 | Policy implication year: 2015 | 0.19 | 22.21 | 6.81 | 6.86 | 0.00 |
| 6 | D4 | Proportion of coal consumption replaced by natural gas in fuel consumption: 70% in 2020 and 90% in 2030 | 0.17 | 15.52 | 2.77 | 8.32 | 1.89 |
| 7 | P1 | Proportion of electricity generated outside city boundary from 2020: 85% | 0.17 | 6.56 | 18.03 | 3.40 | 11.34 |
| 8 | P13 + P14 | Policy implication year: 2012 for newly-built plants and 2015 for old plants | 0.16 | 0.00 | 52.19 | 0.00 | 0.00 |
| 9 | D2 | Proportion of coal-fired boiler replaced by district heating in fuel consumption: 60% in 2020 and 80% in 2030 | 0.13 | 12.91 | 0.08 | 6.91 | 0.86 |
| 10 | I1 | Increasing rate of energy efficiency: 10% in 2020 and 20% in 2030 | 0.13 | 4.97 | 13.65 | 2.57 | 8.58 |
| 11 | T9 | Policy implication year: 2015 | 0.06 | 0.00 | 17.63 | 0.82 | 0.00 |
| 12 | P9 | Policy implication year: 2015 | 0.04 | 0.00 | 0.00 | 4.39 | 0.00 |
| 13 | P12 | Policy implication year: 2012 | 0.03 | 0.00 | 9.80 | 0.00 | 0.00 |
| 14 | T21 | Proportion of gas vehicles in fuel consumption from 2020: 25%; | 0.02 | 0.13 | 1.96 | 0.37 | 2.46 |
| | +T22 + T23 | Proportion of alternative energy public bus and taxi in numbers: 30% in 2020 and 40% in 2030; | | | | | |
| | +T24 | Proportion of alternative energy private cars in numbers: 2.5% in 2020 and 10% in 2030; | | | | | |
| 15 | T7+T8 | Policy implication year: 2014 for China V and 2020 for China VI | 0.01 | 0.00 | 1.83 | 0.08 | 0.00 |

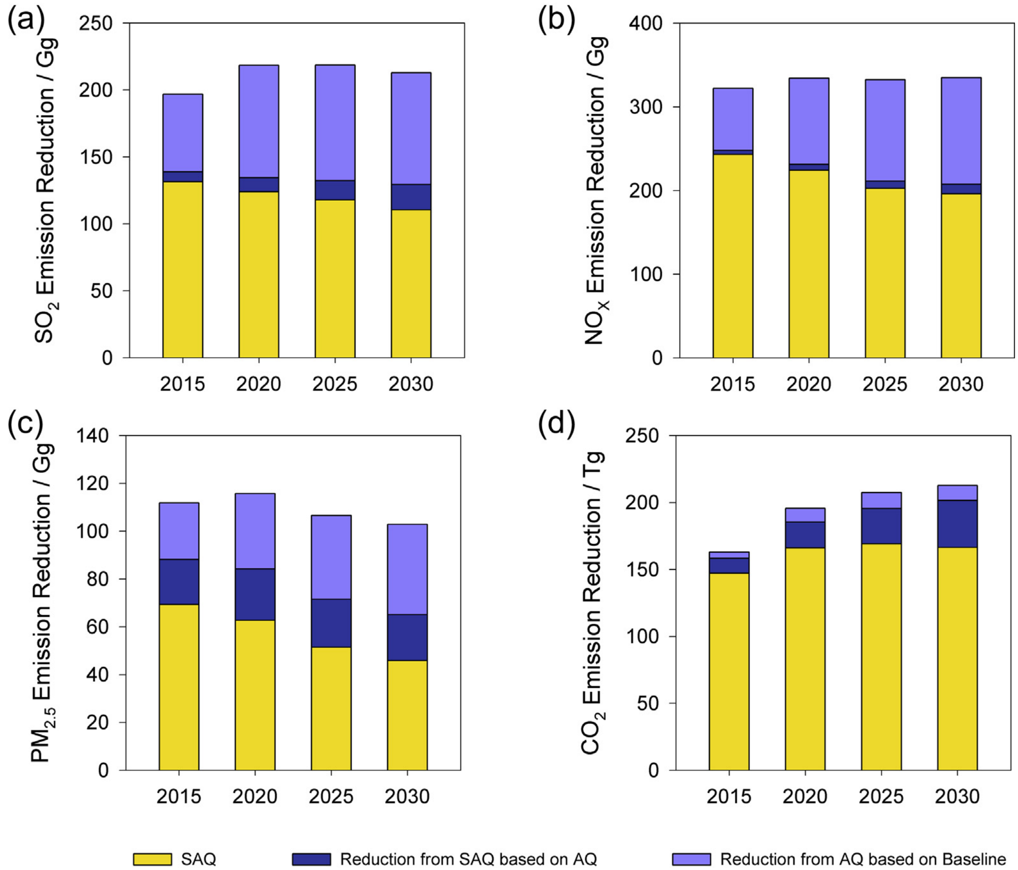


**Fig. 4.** Emission reductions of $SO_2$, $NO_X$, $PM_{2.5}$ and $CO_2$ under policy scenarios.

controlling air pollution and resulting in introduction of stricter (more ambitious and more efficient) set of measures, a scenario referred to as *Strict Air Quality* (SAQ) policy. For example, SAQ additionally introduced installation of fabric filters in newly built power plants. Table 3 presents detailed assumptions about measures introduced in these two scenarios. Some measures are actually a package of several detailed measures, e.g., improvement of energy efficiency in industrial sector could be carried out by usage of renewable energy, higher efficiency of industry machines, production of less waste (Scipioni et al., 2012, 2010) and energy and material recovery (Dias and Arroja, 2012).

Fig. 4 shows the emission reductions of $SO_2$, $NO_X$, $PM_{2.5}$ and $CO_2$ under policy scenarios. In 2030, AQ and SAQ scenario would reduce 84 and 102 Gg of $SO_2$, 128 and 139 Gg of $NO_X$, 38 and 57 Gg $PM_{2.5}$, and 11 and 46 Tg $CO_2$, respectively. The results showed great reduction potential: 39–48% of $SO_2$ emissions, 38–42% of $NO_X$ emissions, 37–55% of $PM_{2.5}$ emissions and 5–22% of $CO_2$ emissions. This showed that air quality measures and policies could also have co-benefits of reducing $CO_2$ emissions. According to the model calculation, the existing air quality policy in Beijing shows fair stringency, as no significant difference between AQ and SAQ scenario was found. The further abatement should rely on cleaner technologies, such as IGCC and CCS, and more aggressive air quality measures by neighboring provinces to control regional air pollution.

## 4. Conclusions

The GAINS-City model inherited the core estimation methodology and structure of the GAINS model, but focuses on city-scale emission estimation and policy evaluation. The model structure has been adjusted to accommodate for specific local circumstances and emission factors were updated reflecting local source characteristics and operating conditions. Consequently, the GAINS-City model is better suited for application at city scale. In addition, a technology-based approach was developed to support the policy evaluation. The new approach allows feedbacks on activity data and explores the co-benefits of air quality and climate policies. A policy list including power plants, industrial combustion, domestic sector, transportation sector and industrial process was proposed, based on a careful review of existing and potential climate-friendly air quality management measures. A reduction index was introduced to rank the priority of policy implementation, which is helpful for policy-makers to design policy package and determine the stringency and timeline for policy implementation.

A case study of Beijing was conducted to demonstrate the features of the GAINS-City model. The baseline scenario relied on the activity data, technology penetrations and projection of socio-economic factors embedded in the GAINS model. Two policy scenarios (AQ and SAQ) were developed based on the ranking of policies according to the established performance index. They aimed to explore the reduction potential of strict implication of existing policy and of implementation of more ambitious and efficient measures. In 2030, analyzed policies could contribute reductions of 39–48% of $SO_2$ emissions, 38–42% of $NO_X$ emissions, 37–55% of $PM_{2.5}$ emissions, and 5–22% of $CO_2$ emissions, respectively.

GAINS-City framework could be applied to other large cities, due to its independent model structure and proposed policy list that are considered essential in most Chinese cities. The large number of source categories included in the model and diverse list of policies focusing on primary sources could support the emission estimation and co-benefits analysis for several cities. A necessary condition for application of this tool is availability of key activity data and technology distribution information for the base year. To enable calculation of air pollutant concentrations and their impacts, collaboration with a group running atmospheric transport model (e.g., CMAQ) is required. As a matter of fact, we have already initiated work on application of GAINS-City for Jinan city where the above steps and analysis are under way.

Compared to GAINS model, current GAINS-City model have no air quality impact and cost analysis modules. But in the final stages of the GAINS-City project, we simulated the air quality in Beijing under different scenarios discussed above using the Community Multi-scale Air Quality Model (CMAQ). Further work is needed to validate these results and follow up with the development and implementation of transfer matrices in the GAINS-City model. Finally, estimating costs for the developed measures that would consider specific local factors should be a high priority for future development. Completing the above tasks would allow for calculation of concentrations and application of the GAINS optimization module to find least cost solution to achieve specific target concentrations.

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