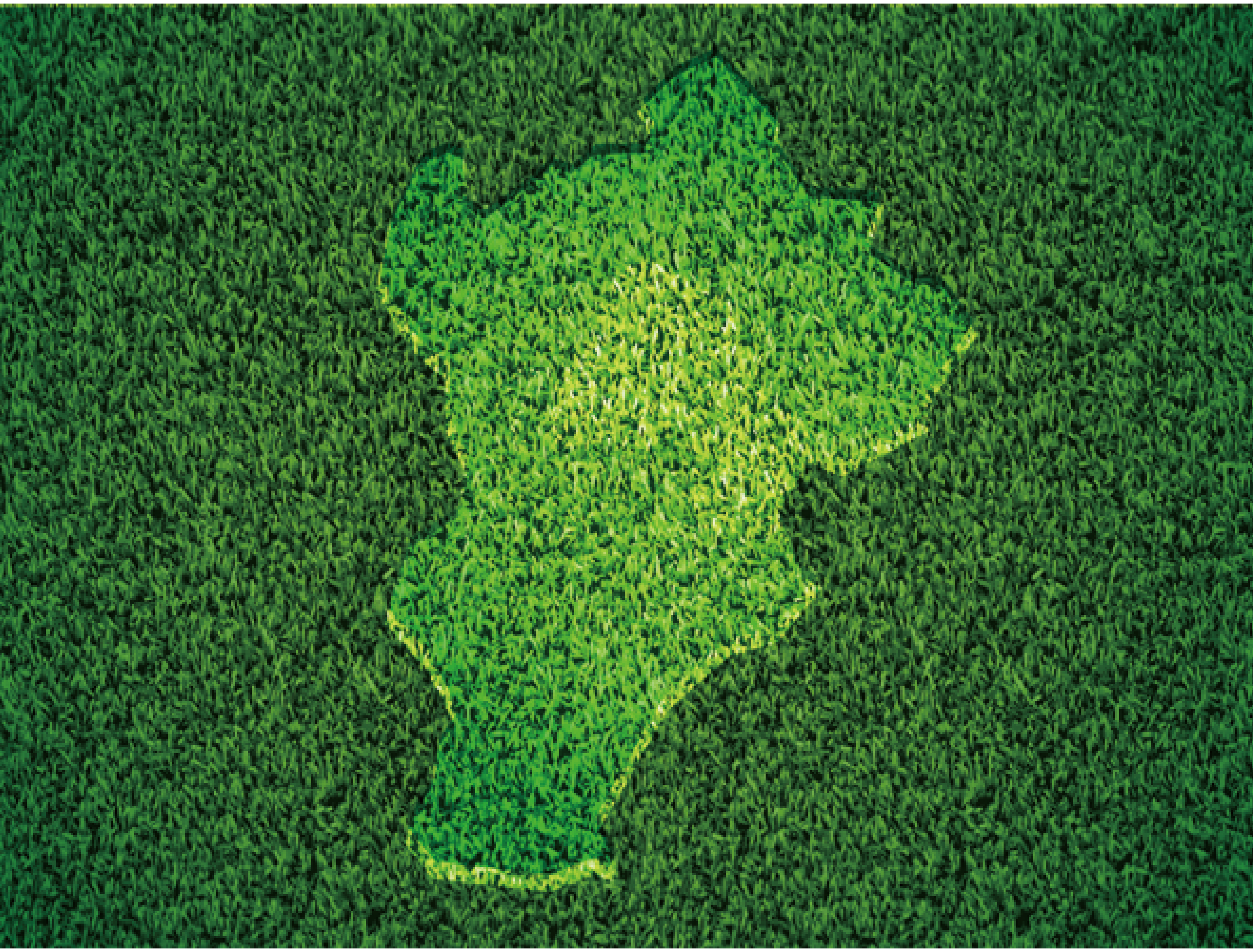
Beijing-Tianjin-Hebei AQM Policy Report Series

中国清洁空气联盟
Clean Air Alliance of China

Can Beijing, Tianjin and Hebei Achieve Their $PM_{2.5}$ Targets by 2017?

Assessment of the potential for air quality improvements in the Beijing-Tianjin-Hebei region under China's new air pollution action plan



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CAAC Policy Reports are a series products to provide insights, analysis and recommendations based on China's air pollution control policies and management practices, to support the clean air work. The CAAC Policy Reports series are compiled by the CAAC secretariat in collaboration with CAAC members and experts.

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Summary of Findings

China's State Council has set new $PM_{2.5}$ improvement targets for Beijing-Tianjin-Hebei area in the new *Air Pollution Prevention and Control Action Plan* (Henthforce, the **Action Plan**). These targets are to achieve 25% reduction of annual mean $PM_{2.5}$ concentrations for the Beijing-Tianjin-Hebei region from 2012 to 2017, and 60μg/m^3 of the $PM_{2.5}$ concentration for Beijing in 2017). To achieve the $PM_{2.5}$ improvement targets, Tianjin and Hebei should propose more stringent control measures than their issued action plans to further reduce NO_X, VOCs and NH_3 emissions.

In this study, we combined Beijing-Tianjin-Hebei regional emission inventories and Community Multi-Scale Air Quality (CMAQ) modeling to evaluate the air quality improvement effect in the region under the measures proposed in the local air pollution action plans for the period from 2012-2017. We found emissions level for the year 2017 using emission inventory from 2012 as the baseline and then estimated the effects of control measures of the local action plans issued by the central government and also the local governments of Beijing, Tianjin and Hebei. We put the emission inventory in CMAQ model to quantify $PM_{2.5}$ reduction effects in the region.

Model results showed[1] that the $PM_{2.5}$ concentration in Beijing, Tianjin and Hebei would decline from 88.3μg/m^3, 112.7μg/m^3 and 112.9μg/m^3 in year 2013 to 65.8μg/m^3, 91.6μg/m^3 and 96.3μg/m^3 in year 2017, respectively. The corresponding decline rates are 25.6%, 18.7% and then 14.7%.[2]

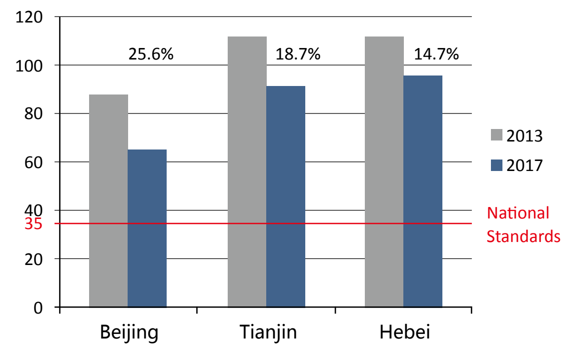

Fig. 1 Simulated $PM_{2.5}$ improvement under the Action Plan (ug/m^3)

These results indicated that significant improvements of air quality in the Beijing-Tianjin-Heibei region can be achieved in 2017 if the local action plans are fully implemented, but there are risks that they might fail to achieve the $PM_{2.5}$ target (Beijing: 60μg/m^3, Tianjin and Hebei: 25% decline) from the **Action Plan**. The measures in the local aciton plans could reduce the emissions of SO_2, NO_X, $PM_{2.5}$ and VOC at rates of 32%, 21%, 24%, 6%, respectively. However, more measures should be proposed in order to reach the **Action Plan** targets, to reduce emission of SO_2, NO_X, $PM_{2.5}$, NH_3, and VOC to 40%, 40%, 35%, 20%, and 30%, respectively.

1. We mainly consider measures that could be quantified in the Action Plan, so our estimates are conservative. Measures of the residential sector and control measures on VOC and NH_3 in the Action Plan are hard to quantify, which, if quantified, should result in more detailed numbers.
2. The evaluation of the Action Plan targets will base on 2013 $PM_{2.5}$ data.The simulated $PM_{2.5}$ concentration reductions from 2013 to 2017 are based on emission reductions from 2012 to 2017, using the same meteorological field to reflect the effects of emission reduction. Here we use the meteorological field for 2013 as there was a lack of $PM_{2.5}$ monitoring data in 2012 for model evaluation, the impacts of meteorology will be discussed later.

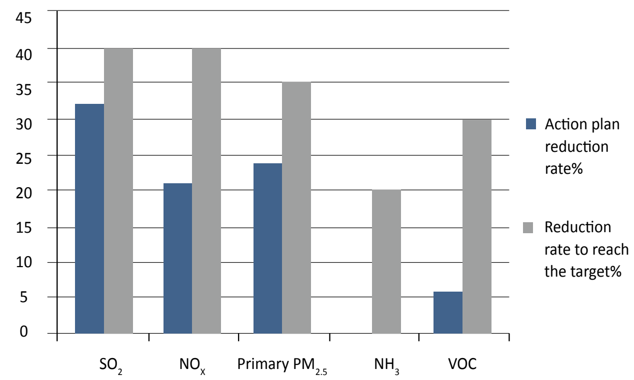

Fig.2 Simulated $PM_{2.5}$ Improvement under the action plans (ug/m^3)

This report recommends ten enhanced measures to ensure the Beijing-Tianjin-Heibei region can achieve the $PM_{2.5}$ improvement targets set by the central government:

1. The region should increase the coal washing rate to 100% for industry use and ban the use of high-sulfur coal (sulfur content higher than 0.6%);

2. In-use heavy duty vehicles in the region should be equipped with a Diesel Particulate Filter (DPF);

3. Hebei should further cut steel production to reduce coal consumption by 60 million tons instead of the original target of 40 million tons;

4. The steel industry in Hebei and Tianjin should upgrade PM control technologies such as ESP and FAB;

5. Install FAB in cement kilns in Hebei and Tianjin, and install SNCR in cement plants in Hebei;

6. Upgrade the dust collectors in Hebei's coking industry;

7. Install $DeNO_X$ facilities in coal-fired heating plants in Hebei and Tianjin, $DeNO_X$ facilities should be installed in 50% of the coal-fired heating plants in Tianjin;

8. Limit the use of Euro3 diesel vehicles in Hebei & Tianjin; so that diesel consumption could be reduced to below 20% of total consumption;

9. Reduce VOC emissions from key industries by 30%-40% in Tianjin and Hebei , such as the coking, paint, and pharmaceutical industries;

10. Increase the proportion of large scale livestock production to 30%, and promote the use of slow-release fertilizers in Tianjin and Hebei ;

By implementing the measures above, our modeling shows that Beijing, Tianjin and Hebei could achieve the $PM_{2.5}$ improvement targets outlined in the **Action Plan** (shown in Fig. 2).

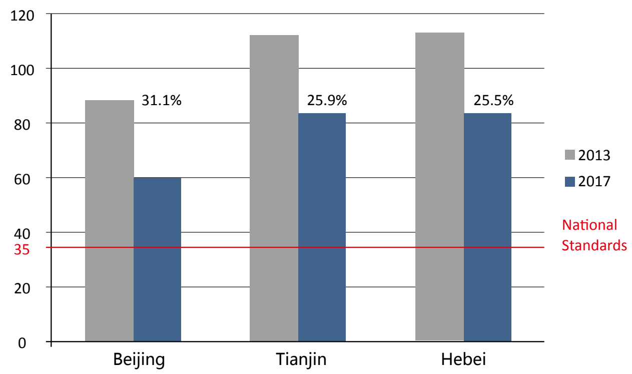

Fig.3 Simulated $PM_{2.5}$ Improvement under the enhanced reduction scenario (ug/m^3)

Other findings:

1. The report firstly use an emissions inventory of the Beijing-Tianjin-Hebei region to analyse the sources of $PM_{2.5}$ in the region. Industrial processes and the residential sector are the main sources of primary $PM_{2.5}$ in the region, accounting for 54% and 29% of the pollution, respectively. Industrial processes include the steel, cement, and coking sectors. The residential sector emissions are from coal and stalk burning. Moreover, the power sector, heating, industrial boiler

and the transportation sector represent the other 4%, 3%, 6% and 4% of the primary $PM_{2.5}$ emissions. SO_2, NO_X, VOCs and NH_3 are the main culprits for secondary $PM_{2.5}$. Industrial boilers, industrial processes (sinter and industrial furnaces), the power sector, the residential sector, and the heating sector contribute 39%, 19%, 17%, 15%, and 8% of SO_2 emissions, respectively. The transportation sector, industrial boilers, the power sector, heating and industrial processes (mainly cement industry) are the main sources of NO_X emissions, accounting for 28%, 27%, 24% ,10% and 7%, respectively. About and 40%, 26% and 9% of VOC emissions are from solvent use, industrial process, and residential sector, and transportation sector, respectively. NH_3 emissions are mainly from N-fertilizer application and livestock farming.

2. Structure adjustment and end-of-pipe control measures are both important for controlling $PM_{2.5}$ pollution. As end-of-pipe control technologies in Beijing are already quite advanced, future emission reductions will be mainly from structure adjustment measures. The potential emission reductions from end-of-pipe measures in Hebei and Tianjin are huge. Hebei and Tianjin can improve air quality further by simultaneously strengthening end-of-pipe control measures and structure adjustment.

3. The region can also decrease greenhouse gas emissions under the **Action Plan** to alleviate climate changes, if Beijing-Tianjin-Hebei region could fully implement the local action plans, CO_2 and black carbon (BC) emissions are estimated to be reduced by 51 million tons and 30 thousand tons under the action plans, and this would mean a decline 5% and 17% from 2012 levels, respectively.

4. Air quality is a regional issue. We found that enhanced emission reductions in Tianjin and Hebei could not only help themselves to achieve their respective targets, but also could benefit air quality in Beijing. Emissions reductions of the neighboring provinces could also benefit Beijing-Tianjin-Hebei region's air quality, However, if these neighboring provinces fail to achieve their targets, the Beijing-Tianjin-Hebei region will then face even greater challenges in achieving their air quality targets.

5. For the model, we are assuming all the measures of the action plans are fully implemented. In reality, there are major obstacles to achieve full implementation. It is crucial for municipal governments of Beijing, Tianjin, and Hebei to make efforts to ensure all the measures are fully executed.

6. Annual fluctuations in meteorological conditions could lead to big differences in $PM_{2.5}$ concentrations. Meteorological factors should be considered for air quality target assessments. Target assessments should use a meterology correction factor, or at least use three-year average assessments of air quality based on international experience to correct for these factors.

7. Beijing, Tianjin, and Hebei should also establish Air Quality Attainment Plans (AQAP). The emissions inventroy used in our reaserch is in regional scale. Local governments could build a more detail emission inventory in AQAP, and do quantitative analysis on pollution reduction. A more accurate air quality improvement assessment could build upon the CMAQ model, and map out a strategy to reach the 2017 target and ultimately reach the *National Ambient Air Quality Standard.*

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1. Methodology

For this study, we first created an emissions inventory for 2012 and then combined it with the Community Multi-Scale Air Quality (CMAQ)[3] model to conduct a simulation for the base year as well as model evaluation. Next, we parameterize the control measures in the action plans to build an emission inventory for 2017, evaluated the potential emission reductions and identified the key measures. The reduction measures specified in the local action plans is finally placed into the simulation to evaluate the potential $PM_{2.5}$ reduction.

1.1 Base year emissions and air quality modeling

We calculated the emission inventories for the base year (2012). Based on our inventory and meteorological data from 2013, The simulation results were then compared with $PM_{2.5}$ monitoring data for the year 2013 (Fig. 1-2). The results show that the model fairly accurately captures the magnitude and spatial variation of $PM_{2.5}$ concentrations in the major cities of the region, which shows that the model could be used as an evaluation tool for air pollution control policies.

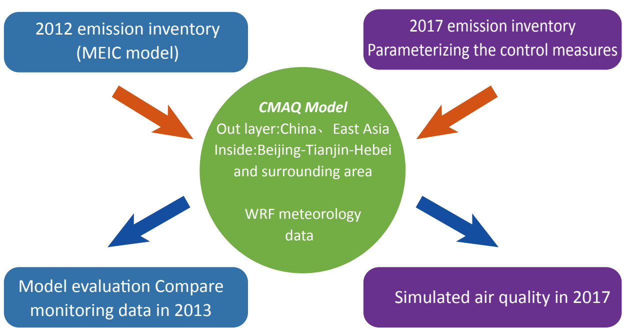


Fig. 1-1 Methodology

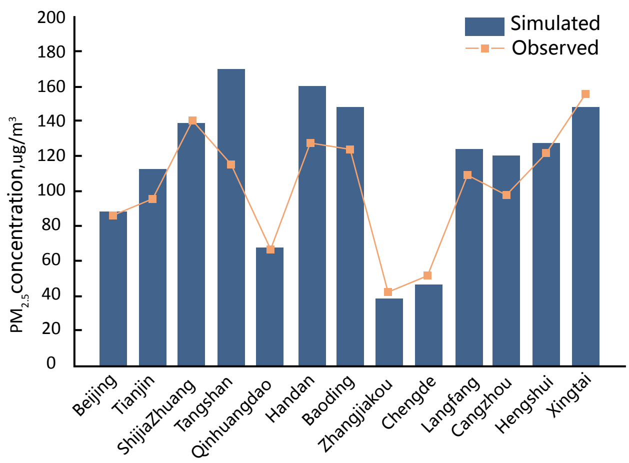


Fig. 1-2 Comparison of simulation results of $PM_{2.5}$ concentrations with actual monitoring data

3. Community Multi-scale Air Quality (CMAQ) model is a third-generation air quality model developed by the U.S. EPA. The CMAQ system can simulate concentrations of tropospheric ozone, acid deposition, visibility, fine particulates, and other air pollutants in the context of a "one atmosphere" approach, involving complex atmospheric pollutant interactions on regional and urban scales.
4. The emission inventory is from MEIC (Multi-resolution Emission Inventory for China, available through http://www.meicmodel.org) developed by Tsinghua University.
5. Monitoring data are from the urban air quality evaluation stations of NAAQM.

2. Pollution reduction evaluation

After the **Action Plan** was announced by the State Council, four ministries jointly released *Rules for the Implementation of the Action Plan on Air Pollution Prevention and Control in Beijing, Tianjin, Hebei and Surrounding Areas*[6]. Local governments also released their implementation plans. For the Beijing-Tianjin-Hebei region, these plans are ***the*** *Beijing Clean Air Action Plan (2013-2017)*[7], the *Tianjin Clean Air Action Plan*[8]*, and the Implementation Scheme for the Action Plan of Air Pollution Prevention and Control for Hebei*[9], which are included in our study. The local action plans outlined a variety of measures, which can be divided into two main categories: structure adjustment measures and end-of-pipe control measures.

To quantify the effects of measures included in the action plans, we estimated future air pollutant emissions based on an emissions inventory of the 2012 and a projection of energy consumption and control technology penetration for the target year according to measures in the local action plans.

2.1 Structure adjustment measures

Structure adjustment measures involve reducing emissions from the front-end, including industrial structure adjustment measures and energy structure adjustment measures. Structure adjustment measures in the local action plans include:

a. Adjusting and optimizing the industrial structure, controlling new capacities of industries with high energy demand and emissions, and decreasing out-dated production capacities while eliminating excess production capacities. These measures would gradually reduce the production capacity of energy-intensive industries.

b. Reducing coal consumption. A coal-dominated energy consumption structure is the main reason for serious air pollution in China, and reductions of coal consumption in Beijing-Tianjin-Hebei region are proposed in the **Action Plan**. By 2017, annual coal consumption in the region shall be reduced by 63 million tons according to the local action plans. This reduction will be 13, 10 and 40 million tons for Beijing, Tianjin and Hebei, respectively, which equate to reducing overall prodction by 61%, 20% and 19%.

c. Clean energy substitution. Natural gas consumption should increase by 50 billion cubic meters, this should translate to 13, 12 and 25 billion cubic meters for Beijing, Tianjin and Hebei , respectively.

d. Restrict vehicle stock numbers. After Beijing implemented controls on vehicle numbers, diesel and gasoline consumption in Beijing will decline in 2017.

Based on the measures mentioned above, we created an energy balance sheet to estimate energy consumption

6. http://www.zhb.gov.cn/gkml/hbb/bwj/201309/t20130918_260414.htm
7. http://zhengwu.beijing.gov.cn/gzdt/gggs/t1324560.htm
8. http://www.tj.gov.cn/zwgk/wjgz/szfwj/201310/t20131009_223397.htm
9. http://www.gov.cn/gzdt/2013-09/12/content_2486904.htm

in 2017, breaking down the consumption patterns by sector and fuel type (see Table 1 in the Appendix).

Detailed structure adjustment measures and the parameterization scheme are summarized in Table 2,3,4 in the Appendix.

2.2 End-of-pipe control measures

End-of-pipe control measures in the local action plans include:

a. Install $DeSO_X$ and $DeNO_X$ equipments for coal-fired power plants, and increase the SO_2 removal efficiency from 80% in 2012 to 90% in 2017.

b. Install $DeSO_X$ equipments in industrial boilers and raise the percent installed to 100% in 2017. Upgrade dust collectors in industrial boilers and phase out low-efficiency WET devices.

c. Install $DeNO_X$ equipments in cement plants and raise the installed percentage from 16% in 2012 to 100% in 2017.

d. Install $DeSO_X$ equipments in sinter plants and raise the installed percentage from 35% in 2012 to 100% in 2017.

e. Implement Euro5 vehicle standards in 2015 for the whole region and, implement Euro6 vehicle standards in 2016 for Beijing.

f. Phase out 2 million yellow label vehicles in the region before 2017. Also, phase out gasoline vehicles and diesel vehicles that do not meet the Euro3 standards.

g. Reduce VOCs emissions from key industries by 20%.

h. Install Stage I and Stage II vapor recycle systems in oil stations.

Detailed end-of-pipe control measures and the parameterization method are summarized in Table 5,6,7, and 8 in the Appendix.

2.3 Air pollution emissions in 2017

2.3.1 Sources of air pollutants

Industrial processes and the residential sector are the main sources of primary $PM_{2.5}$ in the region, accounting for 54% and 29% of the pollution, respectively. Industrial processes include the steel, cement, and coking sectors. The residential sector emissions are from coal and stalk burning. Moreover, the power sector, heating, industrial boiler and the transportation sector represent the other 4%, 3%, 6% and 4% of the primary $PM_{2.5}$ emissions.

SO_2, NO_X, VOCs and NH_3 are the main culprits for secondary $PM_{2.5}$. Industrial boilers, industrial processes (sinter and industrial furnaces), the power sector, the residential sector, and the heating sector contribute 39%, 19%, 17%, 15%, and 8% of SO_2 emissions, respectively. The transportation sector, industrial boilers, the power sector, heating and industrial processes

10. Secondary $PM_{2.5}$ includes sulfates, nitrates, ammonium salts and other inorganic particles. Secondary $PM_{2.5}$ is formed from various gaseous pollutants (precursors), such as SO_2, NOx, VOC, NH_3, etc., through a complex chemical reaction in the atmosphere.

(mainly cement industry) are the main sources of NO_X emissions, accounting for 28%, 27%, 24% ,10% and 7%, respectively. About and 40%, 26% and 9% of VOCs emissions are from solvent use, industrial process, and residential sector, and transportation sector, respectively. NH_3 emissions are mainly from N-fertilizer application and livestock farming.

2.3.2 Total emission reduction

After full implementation of the action plans, the emissions of SO_2, NO_X, $PM_{2.5}$, BC, OC, and VOCs in Beijing-Tianjin-Hebei region in 2017 are estimated to be 1.395Mt, 2.212Mt, 0.902Mt, 0.147Mt, 0.236Mt, and 1.999Mt, respectively. The comparable reduction rates in 2012 are 32%, 21%, 24%, 17%, 14%, and 6%, respectively. Among these three provinces, Hebei's contribution to the emission reductions in the region is the largest due to its high percentage of emissions, accounting for 71%, 71%, 74% and 45% of SO_2, NO_X, primary $PM_{2.5}$, and VOCs reductions, respectively. The emission reduction rates in Beijing are the highest due to the most stringent control measures in the region.

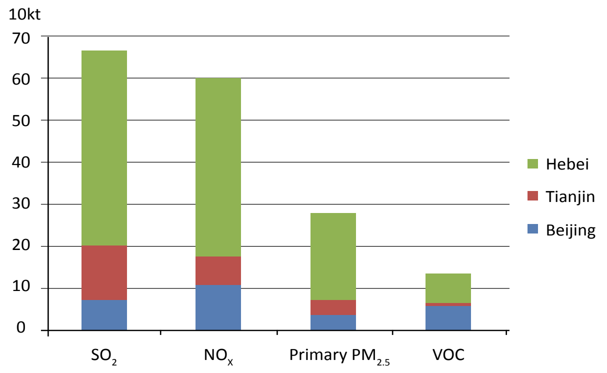
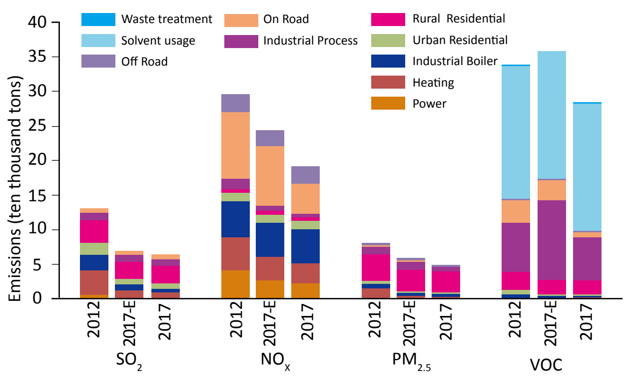


Fig. 2-1 Contributions to total emission reduction in Beijing-Tianjin-Hebei region

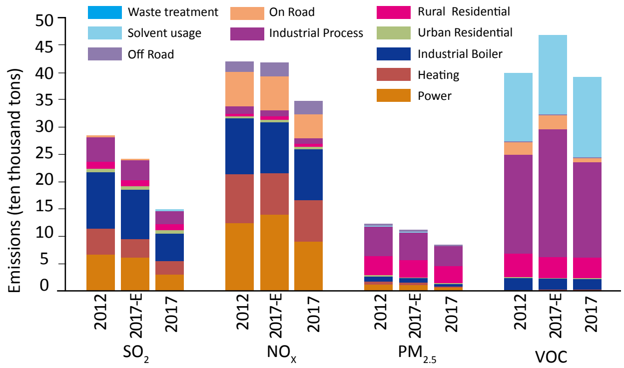
2.3.3 Emissions reduction rates in each province

We focus on emission changes of SO_2, NO_X, NH_3, $PM_{2.5}$, BC, OC and VOCs. Emission changes of each pollutant in Beijing, Tianjin, and Hebei are shown in Fig. 2-2. To separate the effect of structure adjustment measures from end-of-pipe control measures, we conducted two scenarios for 2017, including a scenario that only implements structure adjustments measures (2017-E) and a scenario that further implements end-of-pipe measures (2017). Structure adjustment measures and end-of-pipe control measures in the local action plans for Beijing, Tianjin and Hebei and the corresponding emission reductions are summarized in Table 9 in the Appendix.

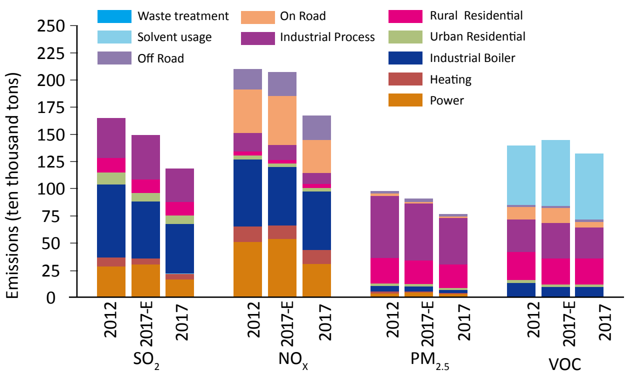
As shown in Fig. 2-2, under the planned measures in the local action plans, Beijing and Tianjin could reduce almost 50% of SO_2 emissions, while Hebei's SO_2 reductions are slightly smaller; emissions of NO_X and primary $PM_{2.5}$ would be reduced considerably in these three provinces, while reduction rates of VOCs are relatively smaller (Hebei and Tianjin are smaller than 5%).



(a) Beijing



(b) Tianjin



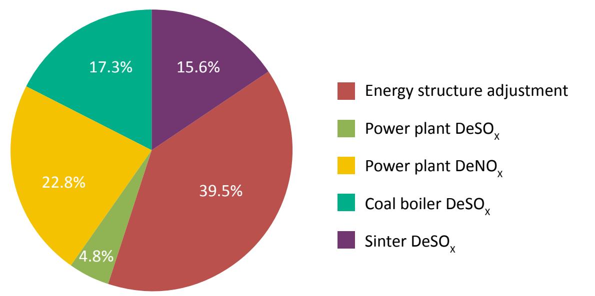
(c) Hebei

Fig. 2-2 Emissions level changes in Beijing, Tianjin and Hebei

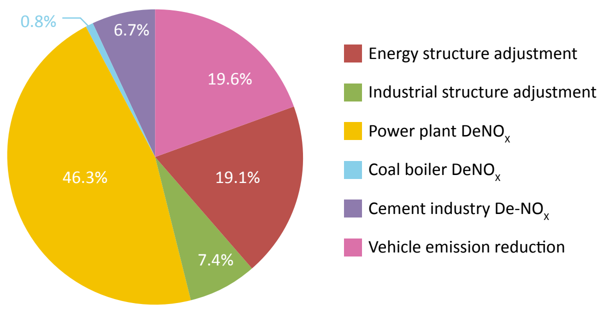
As shown in Fig. 2-2, structure adjustment measures are effective at reducing SO_2 emissions for each of the three provinces, but are less effective at reducing NO_X emissions in Tianjin and Hebei compared to Beijing. These discrepancies could be explained by the fact that Tianjin and Hebei face bigger challenges in terms of adjusting their industrial structure and energy structure. If Tianjin and Hebei could further cut down productions of energy-intensive industries and increase the proportion of clean energy use, more reductions could be achieved. For controlling VOCs emissions, structure adjustment measures have few effects.

2.3.4 The Impact of each measure on emission reduction

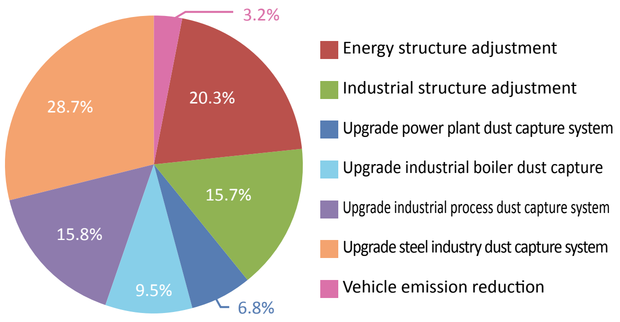
As shown in Fig. 2-3, for the Beijing-Tianjin-Hebei region, the most effective control measures for SO_2 emission reductions are energy structure adjustment measures (accounting for 39.5% of total SO_2 reductions), followed by desulfurization in the power sector (22.8%); the most effective control measures for NO_X emission reductions are power sector denitration (accounting for 46.33% of total NO_X reductions), followed by reductions from vehicles (19.6%) and energy structure adjustment measures (19.1%). The most effective control measures for primary $PM_{2.5}$ emission reductions are upgrades of dust collectors in the steel industry (contributing to 28.7% of primary $PM_{2.5}$ reductions), and also measures to adjust the energy structure adjustment measures (20.3%).



(a) SO_2



(b) NO_X

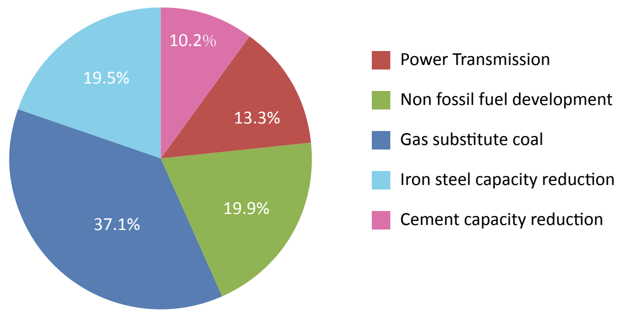


(c) Primary $PM_{2.5}$

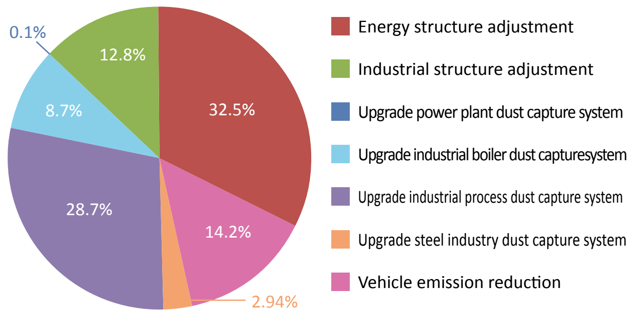
Fig. 2-3 The contributions of each measures on emission reduction

2.3.5 Co-benefits on Greenhouse gas mitigation

Greenhouse gas mitigation could also be achieved under the air pollution action plans. CO_2 emissions and BC emissions in Beijing-Tianjin-Hebei region in 2017 are estimated to be reduced by 51 million tons and 30 thousand tons under the action plans, and decline 5% and 17% from 2012 levels. Energy structure adjustment measures (i.e., shifting from coal to gas, developing non-fossil energy and electricity imports) and industrial structure adjustment measures (i.e., control steel and cement production capacities) contribute 70% and 30% of CO_2 emission reductions in the region, respectively. Structure adjustment measures, upgrading of dust collectors in each industry, and vehicle control can contribute 45%, 41% and 14% of BC emission reductions, respectively.



(1) CO_2



(2) BC

Fig. 2-4 The contributions of each measures on greenhouse gas emission reduction

3. Air quality improvement effect

3.1 Simulated air quality in 2017

To assess air quality improvement effects under the **Action Plan**, two CMAQ simulations (Fig. 3-1) were conducted based on the base year (2012) emission inventory and the target year (2017) emission inventory under the action plans, respectively. We also consider the influences of the surrounding regions on emissions levels in the Beijing-Tianjin-Hebei region. Emissions level changes in the surrounding regions are estimated based on the targets set for these provinces in the **Action Plan**, e.g. reduction of $PM_{2.5}$ by 20%, 20%, and 10% concentrations for Shandong, Shanxi, and Inner Mongolia, respectively. We used the same meteorological data for the base year and the target year (2013 and 2017).

The $PM_{2.5}$ concentrations for each city from the simulation were calculated based on the spatial statistics of the model grid. Model results showed that the $PM_{2.5}$ concentrations in Beijing, Tianjin and Hebei can decline from 88.3μg/m^3, 112.7μg/m^3 and 112.9μg/m^3 in 2012 to 65.8μg/m^3, 91.6μg/m^3 and 96.3μg/m^3 in 2017, respectively. The represents declines of 25.6%, 18.7%, and 14.7%, respectively (Fig. 3-2).

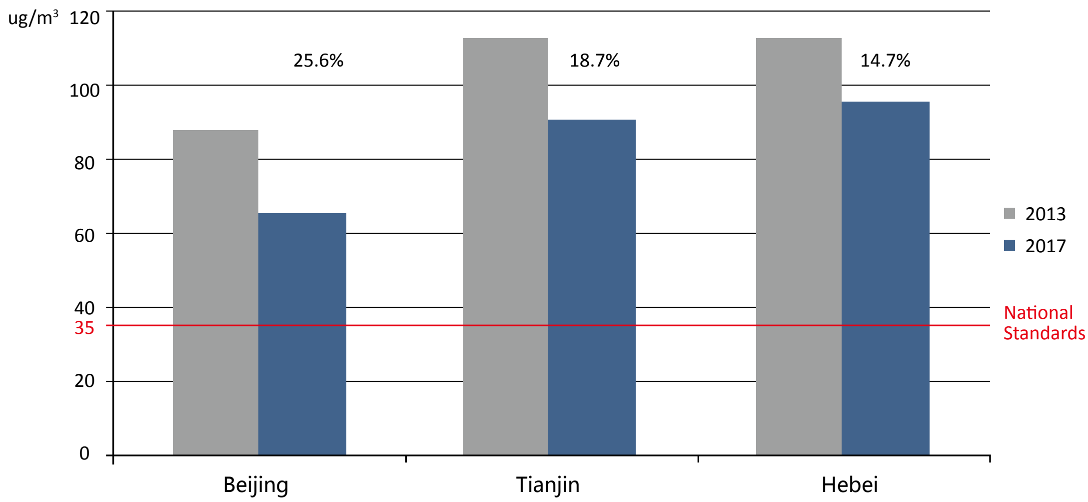


Fig. 3-1 $PM_{2.5}$ improvements from measures in the local action plan

The model results show that significant improvement of particulate air quality in the region can be achieved under the action plans, especially for Beijing, but there is still the risk that Beijing cannot achieve the 60μg/m^3 target and that Tianjin and Hebei cannot reach the 25% decline in $PM_{2.5}$ by 2017.

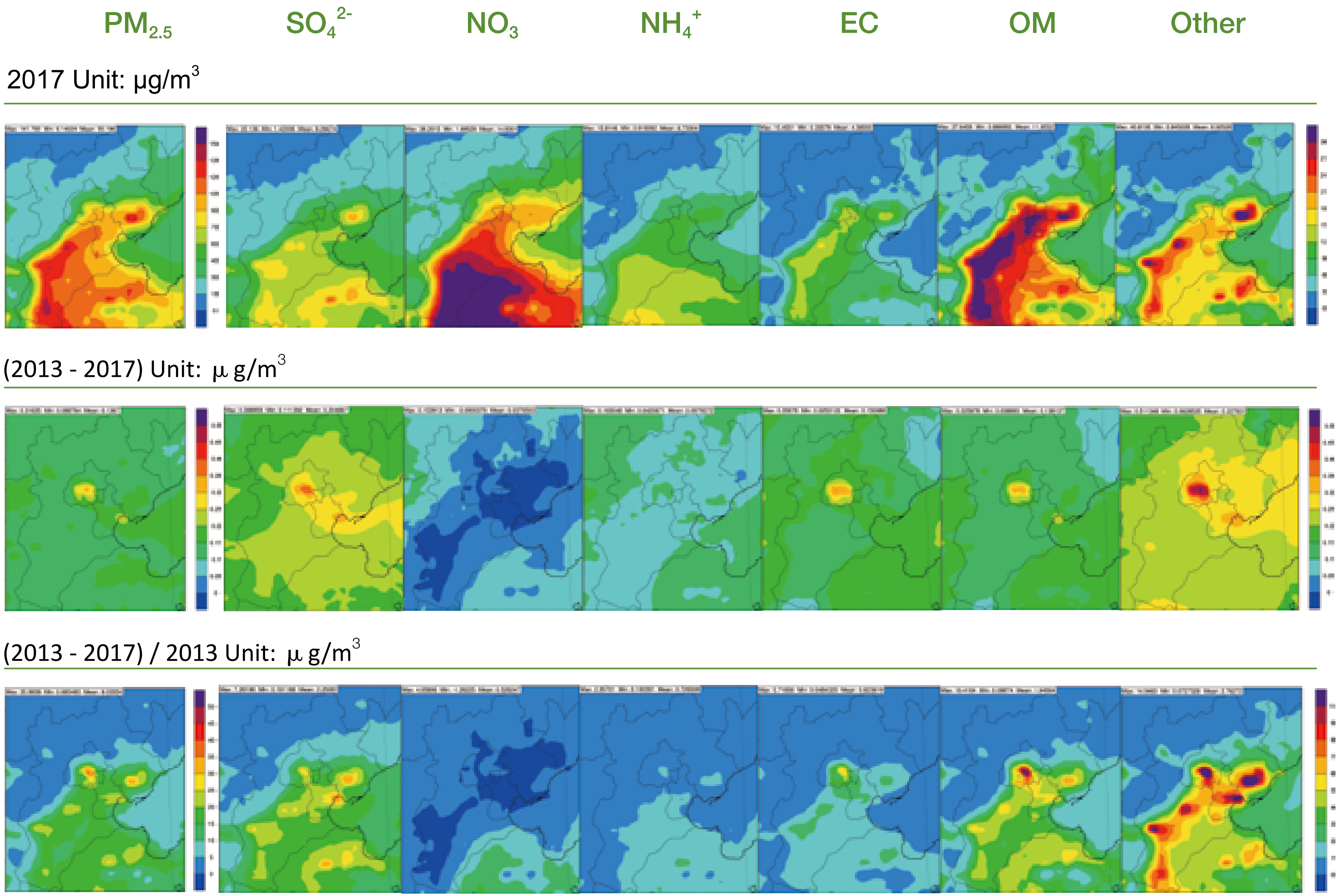


Fig. 3-2 Simulated annual mean concentration changes of $PM_{2.5}$ and its components from 2013 to 2017 in Beiing-Tianjin-Hebei region

3.2 The contribution of $PM_{2.5}$ components decline

The decline of sulfate and other $PM_{2.5}$ components would dominate the changes of $PM_{2.5}$ concentrations (Fig. 3-3), while nitrate concentrations changed slightly. For Beijing, achieving a decline of BC and OM is also important.

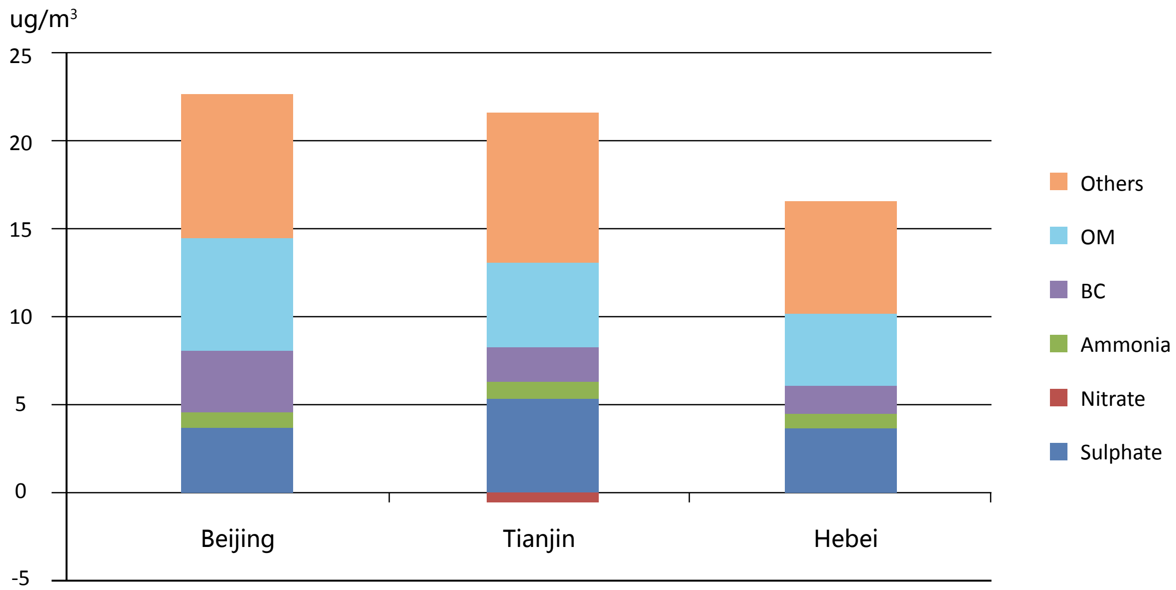


Fig. 3-3 Contributions of each component to the $PM_{2.5}$ concentration decline

These results indicated that reductions of primary $PM_{2.5}$ and SO_2 emissions are the most effective control measures from the local action plans to mitigate $PM_{2.5}$ pollution in the region. These effective measures include: reducing coal consumption, installing desulfurization systems, and reducing primary $PM_{2.5}$ emissions in steel and cement industries in Tianjin and Hebei.

We also compared the concentration changes of $PM_{2.5}$ components with the emission changes of $PM_{2.5}$ precursors, and we found that:

----The sulfate concentrations in Beijing, Tianjin and Hebei declined by 33.3%, 29.5% and 23.1%, but significantly less than the reduction rates of SO_2 emissions (i.e. 51.4%, 47.3% and 28.1%, respectively).

----The change in nitrate concentration in Beijing and Hebei was close to zero. Tianjin had an increase rate of 2.9%, which is not consistent with the NO_X emission change.

----The declining rates of OM concentration in Beijing are 27.5%, higher that Tianjin (17.4%) and Hebei (14.0%).

The control measures in the local action plans are quite effective in reducing SO_2 emissions, but have limited potential in decreasing levels of NO_X and primary $PM_{2.5}$, and the controls of VOCs and NH_3 are also much weaker. Emissions of $PM_{2.5}$ precursors should decline by more than 25% in Beijing, which will also lead to a significant decline in $PM_{2.5}$ concentration levels. Emission reduction rates are less in Hebei than in Beijing and Tianjin. The reduction rates of NO_X and $PM_{2.5}$ in Hebei are only 20.2% and 21.4%, which is lower than the $PM_{2.5}$ reduction target of 25%.

Moreover, the concentration changes of some $PM_{2.5}$ components (e.g. nitrate) that result from emission changes of precursors present a significant nonlinear relationship. For example, NO_X emissions are to be reduced by 34.9%, 17.3%, and 20.2% in Beijing, Tianjin, and Hebei, respectively. Whereas nitrate concentrations are projected to decrease very slightly or even increase. Values of GR indicate that the Beijing-Tianjin-Hebei region is rich in NH_3 (GR>1)[11], which is consistent with previous studies[12.13.14]. Formation of secondary inorganic aerosols (SIA) is more sensitive to the atmospheric oxidation capacity under NH_3-rich conditions. Since the region is also located in high VOC-concentration area [1113], the NO_X emission reductions are expected to result in an elevated level of O_3 and HO_X radicals[15], which increase the formation of SIA. In addition, the lower emission reduction rates outside the region and the constant biogenic VOC emission rates are also reasons that concentration reduction rates are smaller than the changes in emission levels.

11. Zhang et al., Probing into regional O_3 and PM pollution in the U.S., part II. An examination of formation mechanisms through a process analysis technique and sensitivity study. J. Geophys. Res. 2009, 114(D22305), DOI: 10.1029/2009JD011900.,GR>1 means rich in NH_3
12. Liu, X. H., et al. (2010), Understanding of regional air pollution over China using CMAQ, part II. Process analysis and sensitivity of ozone and particulate matter to precursor emissions, Atmos. Environ., 44, 3719–3727
13. Wang et al. Sulfate-nitrate-ammonium aerosols over China: response to 2000–2015 emission changes of sulfur dioxide, nitrogen oxides, and ammonia, Atmos. Chem. Phys., 13, 2635–2652, 2013
14. Zhao et al. Impact of national NO_X and SO_2 control policies on particulate matter pollution in China, Atmos Environ, 2013, 77: 453-463
15.Introduction to Atmospheric Chemistry, by Daniel J. Jacob, Princeton University Press, 1999.

4.Enhanced reduction scenario

4.1 Emission Reductions Required for Achieving the $PM_{2.5}$ Targets

We further designed an enhanced reduction scenario to get safeguard measures for achieving the $PM_{2.5}$ reduction targets in the **Action Plan** based on the analysis in 3.3.

Under the enhanced reduction scenario, the emission reduction rates of SO_2, NO_X, $PM_{2.5}$, NH_3, and VOCs are as large as 40%, 40%, 35%, 20%, and 30%, respectively. As better control of SO_2 and primary $PM_{2.5}$ could significantly alleviate the $PM_{2.5}$ pollution in the region, we propose that the control measures for primary $PM_{2.5}$ should be strengthened in Tianjin and Hebei. More stringent control measures of NO_X, VOCs, and NH_3 are introduced to reduce nitrates and ammoniums. Fig. 4-1 shows the $PM_{2.5}$ concentration changes under the enhanced reduction scenario. Fig. 4-2 shows the emission reduction rates of each type of pollutants needed to achieve the $PM_{2.5}$ targets, and the corresponding concentration changes of each $PM_{2.5}$ component.

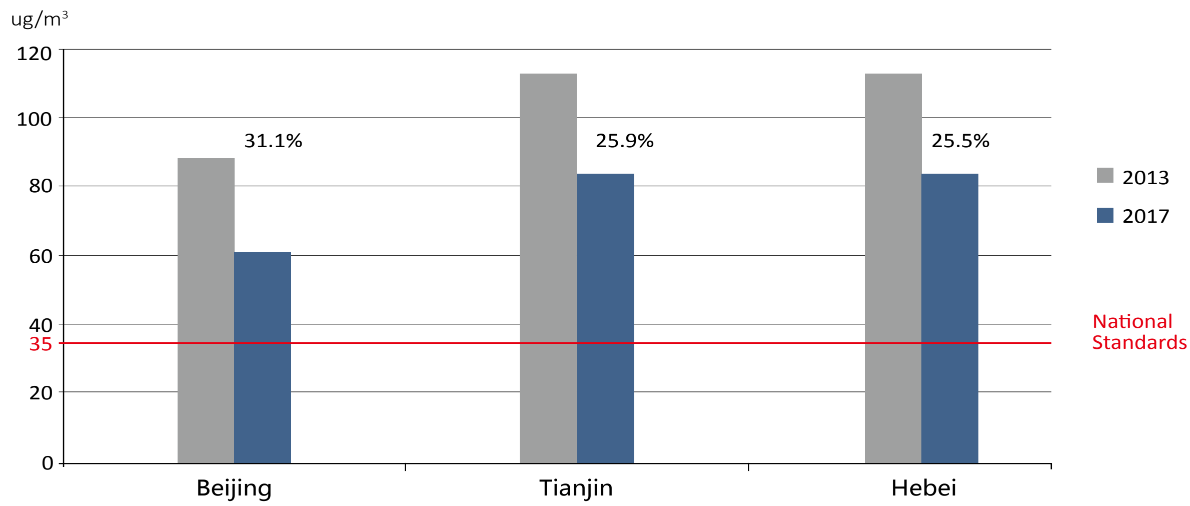


Fig. 4-1 Improvement on $PM_{2.5}$ pollution in the Beijing-Tianjin-Hebei region under the enhanced reduction scenario

A comparison of an enhanced reduction scenario (ERS) with reductions in both pollutants with the local action plan scenario (APS) is shown in Fig. 4-2. Under the ERS, the concentrations of major $PM_{2.5}$ components are expected to decline by more than 25%. However, the declining rates of nitrates and ammoniums are still less than 25%, and the concentrations of nitrates are higher than other components in 2017. Because the measures to control ammonia are still limited, even under the enhanced reduction scenario (20% ammonia reduction), the potential for reduction in nitrate is also small.

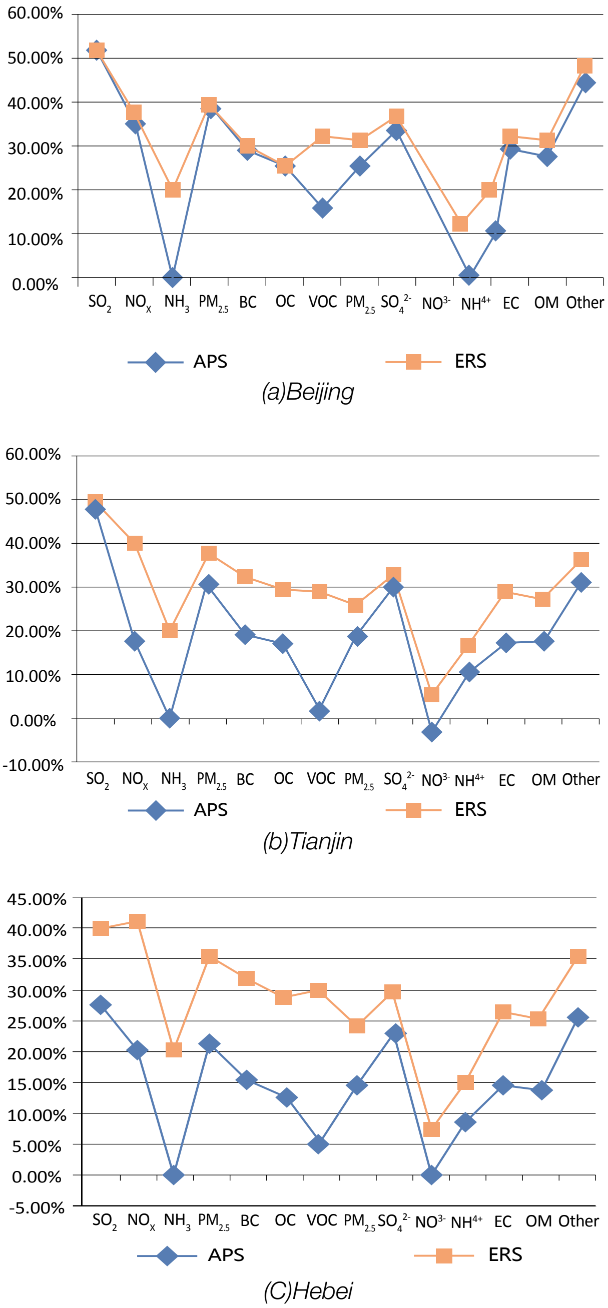


Fig. 4-2 Reduction rates of each air pollutant emission and each $PM_{2.5}$ component

4.2 Policy implication

Controlling emissions of SO_2 and primary $PM_{2.5}$ could lower $PM_{2.5}$ concentrations significantly. Tianjin and Hebei should further control primary $PM_{2.5}$ emissions in order to achieve the environmental targets in the **Action Plan**.

NO_X, VOCs, and NH_3 emissions should be reduced simultaneously to mitigate the SIA concentrations, especially for nitrates.

The residential sector, industrial process, solvent use, fertilizer use, and livestock[16] are the main emission contributors to the emissions of primary $PM_{2.5}$, VOCs, and NH_3, respectively. It is still hard to parameterize the measures of residential sector and VOCs and NH_3 control measures on in the local action plans , further research should be pursued to achieve a greater level of understanding and detail on these topics.

4.3 Proposed measures

According to the emission reduction targets set by the enhanced reduction scenario, we recommend enhanced measures to further reduce pollution:

1. The region should increase the coal washing rate to 100% and ban the use of high-sulfur coal (coal with a sulfur content higher than 0.6%);

2. In use heavy duty vehicles in the region should be equipped with Diesel Particulate Filters (DPF);

16. Huang et al. A high-resolution ammonia emission inventory in China, Global Biogeochem. Cycles, 2012, 26, GB1030, doi:10.1029/2011GB004161

3. Hebei should cut steel production to reduce coal consumption by 60 million tons instead of the original target of 40 million tons;

4. The steel industry in Hebei and Tianjin should upgrade PM control technology to technologies such as ESP and FAB;

5. Install FAB in cement kilns in Hebei and Tianjin and install SNCR in cement plants in Hebei;

6. Upgrade the dust collectors in Hebei's coking industry;

7. Install DeNOx facilities in coal-fired heating plants in Hebei and Tianjin. DeNOx facilities should be installed in 50% of thcoal-fired heating plants in Tianjin;

8. Limit the use of Euro3 diesel vehicles in Hebei and Tianjin; so that diesel consumption could be reduced to below 20% of total consumption;

9. Reduce VOCs emissions from key industries by 30%-40% in Tianjin and Hebei, such as the coking, paint, and pharmaceutical industries;

10. Increase the proportion of large-scale livestock production by 30% and increase the use of slow-release fertilizers in Tianjin and Hebei.

5. Uncertainty analysis

For our analysis, we only considered the measures that could be quantified in the local action plans, which means that our results are conservative estimates. To identify other factors that might have important impact on the $PM_{2.5}$ pollution in the region, we conducted an uncertainty analysis. These factors are:

5.1 The impact of annual fluctuation of meteorological condition

We use the 2013 meteorology data for the baseline scenario, but studies have shown that the meterological conditions in 2013 were extremely bad for preventing air pollution.

To avoid the influence of meteorological conditions on the effects of the control measures, a meteorology correction factor should be used for the assessment. Another method to isolate the impacts of the control measures is to use a three-year average air quality assessment based on international experience.

5.2 The impacts of emission reductions from the neighboring regions

In this study, we assumed that the targets for the provinces surrounding Beijing-Tianjin-Hebei region (e.g. 20%, 20%, and 10% reduction of $PM_{2.5}$ concentrations for Shandong, Shanxi, and Inner Mongolia) could be achieved. But if the emissions of the neighboring provinces still remain the same level as 2012, the $PM_{2.5}$ concentration of Beijing, Tianjin and Hebei in 2017 would be increased by 1.9μg/m^3, 3.9μg/m^3, and 3.5μg/m^3 compared to the result of APS, and the reduction rates of $PM_{2.5}$ concentrations would be increased by 2~4%, (sulfates and ammoniums would increase by 6%~8% and 4%~5%). This indicates that controls in these surrounding regions are important for the reduction of secondary $PM_{2.5}$ concentrations in the Beijing-Tianjin-Hebei region.

5.3 Measures on VOCs and NH_3 are hard to quantify

Measures of the residential sector and control measures on VOCs and NH_3 in the **Action Plan** are still vague, they need to be more specified. There should be increased control measures to decrease NO_X, VOCs, and NH_3 to improve air quality in the region.

Appendix

Table 1 Regiional structure adjustment measures parameterization scheme (Unit:10kt)

Sector	Fuel/ Products	2012			2017		
		Beijing	Tianjin	Hebei	Beijing	Tianjin	Hebei
Power	Coal	651	2746	9666	0	2346	9390
	NG a	21	1	0	64	49	15
Heating	Coal	606	1016	1469	217	738	1065
	NG	14	0	1	40	26	33
Industrial	Coal	424	1791	15561	224	1495	12595
	NG	14	16	25	29	35	139
	steel	2.6	2124	18048	3	1700	16299
	cement	875	784	12810	360	676	9615
Urban residential	Coal	218	78	908	98	62	668
	NG	38	12	15	59	18	47
	LPG	27	7	77	48	12	114
Rural residential	Coal	371	115	1140	291	104	1026
	NG	0.3	0	0	5.02	0	0
	LPG	9	5	6	34	26	153
	Crop	59	313	1677	47	282	1593
	Wood	160	90	724	128	81	688
On road	gasoline	399	128	456	370	160	563
	diesel	211	108	743	194	108	853
Off-road	diesel	46	37	348	47	46	415

a.Unit for NG is 100 million cubic meters.

Table 2 Structure adjustment parameterization scheme (Unit:10kt) : Beijing

Sector	Fuel/ Products	2012	2017	Data sources	Policies
Total	Coal	2270	830		Reduce coal consumption: by 2017, coal consumption should be less than 10 million tons, a reduction of 13 million tons from 2012 levels.
Power	Coal	651	0	Shut down all coal-fired units, so coals used in power sector are estimated to be zero in 2017.	Shut down all coal-fired units, thus reducing 9.2 million tons of coal use: the proportion of clean energy in electricity generation will reach 100%.
Heating	Coal	606	217	Shut down coal-fired heating plants, thus reducing 2.69 million tons of heating coal Cut 2.20 million tons of coal from heating boilers, and an estimated 1.20 million tons from centralized heating boilers .	Cut 2.2 million tons of coal from heating. Switch 137 coal boilers (together about 4,900 t/h) in the six core districts to gas, reducing 1.2 million tons of coal; Coal-fired heating boilers below 20 t/h in suburban district and boilers of commercial services are to switch to clean energy, reducing 1 million tons of coal.
Industry	Coal	424	224	Cut 2 million tons of coal from industrial boilers.	Cut 2 million tons of coal from industrial boilers;boilers in 19 industrial zones (about 2,100 tons) are to switch from coal to gas, reducing 0.5 million tons of coal; boilers from large-scale plants switch coal to gas, boilers in small industrial zones switch to clean energy, reducing 0.55 million tons of coal; cement production capacity should be reduced to 4 million tons, oil refinery capacity should be controlled within 10 million tons, and 1,200 small township enterprises should be shut down, reducing 95 million tons of coal.
	Industrial boilers	218	80		
	Industrial kilns	206	144	Cement production capacity reduced to 4 million tons, is thus estimated to reduce 0.62 million tons of coal.	
Urban residential	Coal	218	98	Reduce 0.2 million tons of residential coal; Cut 1 million tons of coal from distributed residential coal heating boilers.	Cut 1 million tons of residential coal.Dongcheng and Xicheng District are to be coal-free.Speed up the process of urbanization, Reduce residential coal in Chaoyang, Haidian, Fengtai, and Shijingshan Districts.Reduce rural coal. Switch cooking fuel in the rural areas is to gas before the end of 2016. 250 thousand rural households to switch to electricity, gas and renewable energy.
Rural residential	Coal	371	291	Cut 0.8 million tons of urban coal.	
Industry	cement	875	360	Cement production capacity reduced to 4 million tons, and estimating the capacity utilization will increase from 88% in 2012 to 90% in 2017.	Reduce production capacity of cement: production capacity of cement to be reduced to 4 million tons in 2017 from 10 million tons in 2012.
Industry	steel	2.6	2.6		
Urban residential	LPG	27	48	Estimated based on growth trends.	
Rural residential	NG	0.27	5.02	NG consumption is estimated to reach 502 million cubic meters according to relevant departments.	
	Stalk	59	47	estimated to be reduced by 20%.	
	Wood	160	128	estimated to be reduced by 20%.	

Table 3 Structure adjustment parameterization scheme in the Action Plan (Unit:10kt): Tianjin

Sector	Fuel/ Products	2012	2017	Data sources	Policies
Total	Coal	5746	4746		Reduce coal consumption:by 2017, coal consumption should be reduced by 10 million tons.
Power	Coal	2746	2346	Coal-fired units to switch to gas or shut down, reduce 4 million tons of coal.	Coal-fired units to switch to gas or shut down: switch to gas (Chentang, Jinhai and Junliangcheng power plants); shut down (Jianchang power plants).
Heating	Coal	1016	738	Coal-fired heating boilers are to switch to gas or shut down, thus estimating reducing 2.78 million tons of coal.	Coal-fired heating boilers switch to gas or shut down: 465 heating boilers (about 13755 tons) in the core district are switched to gas or shut down before the end of 2016.
Industry	Coal	1791	1495		Coal-fired industrial boilers to switch to gas or combine to grids: coal-fired industrial boilers below 35 tons in the core district and boilers below 10 tons in the suburban district are to switch to gas or combine to grids. Industrial boilers in the industrial zones are to switch to gas or shut down.
	Industrial boilers	766	660	Coal-fired industrial boilers to switch are to gas or shut down thus estimating a reduction 1.06 million tons of coal.	
	Industrial kilns	142	129	Cement production capacity reduced by 2.29 million tons, thus estimating a reduction of 0.13 million tons of coal.	
	Coking	883	707	Steel production capacity reduced to 20 million tons, thus estimating a reduction of 1.76 million tons of coal.	
Urban residential	Coal	78	62	Estimated to be reduced by 20%.	
Rural residential	Coal	115	104	Estimated to be reduced by 10%.	
Industry	Cement	784	676	Cement production capacity reduced by 2.29 million tons, capacity utilization increase from 88% to 90%.	Reduce cement production capacity: phase out 2.29 million tons of out-dated cement production capacities.
Industry	Steel	2124	1700	Steel production capacity reduce to 20 million tons, thus estimating the capacity utilization increase to 85% in 2017.	Reduce production capacity of steel: production capacity of steel should be controlled within 20 million tons.
Urban residential	LPG	7	12	Estimated based on growth trends.	
Rural residential	NG	0	0		
	Crop	313	282	Estimated to be reduced by 10%.	
	Wood	90	81	Estimated to be reduced by 10%.	

Table 4 Structure adjustment parameterization scheme(Unit:10kt): Hebei

Sector	Fuel/ Products	2012	2017	Data sources	Policies
Total	Coal	28744	24744		Reduce coal consumption: By 2017, coal consumption should be reduced by 40 million tons.
Power	Coal	9666	9390	Shut down 29 thermal power units below 100MW (about 637.5 MW), reducing 2.76 million tons of coal use.	Shut down 29 thermal power units below 100MW (about 637.5 MW), reducing 2.76 million tons of coal use.
Heating	Coal	1469	1065	140 million m^2 of centralized heating is to be switched from coal to gas, thus estimating a reduction of 4.04 million tons of coal.	Centralized heating switch coal to gas: about 140 million m^2.
Industry	Coal	15561	12595		
	Industrial boilers	5340	3982	Shut down 11,071 small coal-fired boilers, testimating a reduction of 13.58 million tons of coal.	Shut down small coal-fired boilers. Shut down coal-fired industrial boilers below 35 tons in the core district and boilers below 10 tons in the suburban district. Shut down 11,071 small coal-fired boilers, reducing 13.58 million tons of coal.
	Industrial kilns	1856	1473	Cement production capacity is to be reduced by 61 million tons, estimating a reduction of 3.83 million tons of coal.	
	Coking	8365	7141	To meet the total coal reduction target of 40 million tons for Hebei, the steel industry is required to reduce 12.25 million tons of coal.	
Coal washing	Coal	2168	1030	Ban foreign coal washing, estimated to reduce 11.38 million tons of coal.	Ban foreign coal washing, estimated to reduce 11.38 million tons of coal.
Urban residential	Coal	908	668	Ten thousand tons of residential heating is to switch from coal to gas, thus estimating a reduction of 2.4 million tons of coal.	Residential heating is to switch from coal to gas.
Rural residential	Coal	1140	1026	Estimated to be reduced by 10%.	Reduce rural coal use for cooking and heating.
Industry	Cement	12810	9615	Cement production capacity reduced by 61 million tons, estimating a capacity utilization increase from 70% in 2012 to 80% in 2017.	Reduce production capacity of cement: phase out 61 million tons of out-dated cement production capacities in 2017.
Industry	Steel	18048	16299	Estimated base on the required reductions of steel productions from the required reductions of coal use in steel industry. The capacity utilization should increase from 63% in 2012 to 72% in 2017.	Reduce production capacity of steel: production capacity of steel should be reduced by 60 million tons.
Urban residential	LPG	77	114	Estimated based on growth trends.	
Rural residential	NG	0	0		
	Crop	1677	1593	Estimated to be reduced by 5%.	
	Wood	724	688	Estimated to be reduced by 5%.	

Table 5 Regional end-of-pipe control measures parameterization scheme (Unit: %): stationary combustion sources

Sector	Technology	Control technology	2012			2017			Policies
			BJ	TJ	HB	BJ	TJ	HB*	
Power		FGD	100	99	100	100	100	100	**Action Plan:** All coal-fired power plants are required to install $DeSO_x$ facilities. **Tianjin:** Finish the demolition of flue gas bypass to upgrade $DeSO_x$ of thermal power before the end of 2013. 3.8 GW of power units are required to install or upgrade FGD. **Hebei:** 65 thermal power units from 25 companies (about 14 GW) are required to install FGD.
Power	>300MW	LNB	100	61	69	100	0	0	**Action Plan:** Coal-fired units except CFB units are required to install $DeNO_x$ facilities. **Tianjin:** Coal-fired units equal to or bigger than 200MW are required to install and use $DeNO_x$ facilities before the end of 2014. 5.25 GW of power units are required to install $DeNO_x$ facilities. **Hebei:** 99 thermal power units (about 28 GW) should equipped with denitration facilities. 21.07 GW of power units are required to install $DeNO_x$ facilities.
Power	>300MW	LNB+SCR	0	39	31	0	100	100	
Power	100~ 300MW	LNB	1	28	45	1	10	10	
Power	100~ 300MW	SCR	44	0	8	44	40	40	
Power	100~ 300MW	LNB+SCR	46	0	0	46	50	50	
Power	<100MW	SCR	17	0	6	17	50	61	
Power		WET	0	1	1	0	0	0	**Tianjin:** 3.65 GW of power units are required to upgrade dust collectors. **Hebei:** 88 coal-fired units from 41 companies (about 12 GW) should upgrade dust collectors. 3.51 GW of power units are required to upgrade dust collectors.
Power		ESP	100	99	99	100	74	91	
Power		ESP2	0	0	0	0	26	9	
Power	NG	SCR	0	0	0	25	0	0	**Beijing:** Jingfeng NG power plant should install $DeNO_x$ facilities.
Heating	Pulverized boiler	SCR	0	0	0	100	0	0	**Beijing:** Coal-fired central heating plant should install denitration facilities before the end of 2015.
Industrial boilers		FGD	0	0	0	70	70	16	**Action Plan:** All coal-fired boilers equal to or bigger than 20 tons per hour are required to install $DeSO_x$ facilities. **Hebei:** 114 coal-fired boilers (about 4800 tons) are required to install $DeSO_x$ facilities. 131 boilers (3813 tons) should upgrade $DeSO_x$ facilities and dust collectors.
Industrial boilers	CFB	WET	0	15	26	0	0	7	**Action Plan:** Coal-fired boilers should upgrade dust collectors. **Hebei:** 164 coal-fired boilers (about 5600 tons) should upgrade dust collectors.
Industrial boilers	CFB	ESP	68	85	65	60	90	84	
Industrial boilers	CFB	FAB	32	0	9	40	10	9	
Industrial boilers	Auto grate boiler	CYC	18	32	7	0	0	0	
Industrial boilers	Auto grate boiler	WET	68	60	86	80	80	81	
Industrial boilers	Auto grate boiler	ESP	14	0	0	20	20	19	

*Note: BJ=Beijing, TJ=Tianjin, HB=Hebei

Table 6 Regional end-of-pipe control parameterization scheme (Unit: %): industrial process

Sector	Technology	Control technology	2012			2017			Policies
			BJ	TJ	HB	BJ	TJ	HB	
Industrial process	Precalciner cement kiln	LNB	0	0	0	0	0	0	**Action Plan:** Precalciner cement kilns should be equipped with LNB and install $DeNO_x$ facilities. **Beijing:** All cement kilns are required to install $DeNO_x$ facilities. 8000 tons/day clinker kilns are required to install $DeNO_x$ facilities. **Tianjin:** Cement kilns are required to install $DeNO_x$ facilities. 6000 tons/day cement kilns are required to install $DeNO_x$ facilities. **Hebei:** 67 Precalciner cement kilns (about 62 million tons) should be equipped with LNB and install $DeNO_x$ facilities.
		SNCR	17	0	17	100	40	63	
	Sinter	FGD	0	0	70	100	100	100	**Action Plan:** Sinter plants are required to install $DeSO_x$ facilities. **Tianjin:** 1275 m2 of sintering production lines are required to install desulphurization facilities. **Hebei:** 120 sintering production lines (about 18000m2) are required to install desulphurization facilities.
	Precalciner cement kiln	ESP	3	5	17	0	0	0	**Hebei:** 40 cement production lines (about 23 million tons) should upgrade dust collectors. 5000 tons/day cement kilns should upgrade dust collectors.
		FAB	94	38	58	94	50	60	
		ESP2	3	57	26	6	50	40	
	Lime	CYC	17	0	3	0	0	0	**Action Plan:** Industrial kilns should upgrade dust collectors.
		WET	33	0	23	57	0	85	
		ESP	0	0	6	0	0	6	
		FAB	43	100	9	43	100	9	
	Brick	CYC	5	0	11	0	0	0	
		WET	4	4	0	100	100	100	
	Sinter	CYC	2	2	2	2	0	0	**Tianjin:** Steel companies should upgrade dust collectors. 775m2 of sinter plants should upgrade dust collectors. **Hebei:** 64 steel companies (about 180 million tons) should upgrade dust collectors. 16 million tons of steel companies should upgrade dust collectors.
		WET	18	18	18	18	0	0	
		ESP	67	67	67	67	46	87	
		FAB	13	13	13	13	54	13	
	Iron	FAB	100	100	100	100	100	100	
	BOF steel	ESP	27	27	27	27	17	20	
		FAB	73	73	73	73	83	80	
	EAF steel	CYC	5	5	5	5	0	0	
		WET	50	50	50	50	0	0	
		ESP	19	19	19	19	74	74	
		FAB	26	26	26	26	26	26	

Table 7 End-of-pipe control measures parameterization scheme (Unit: %): VOC sources

Sector	Technology	Control technology	2012			2017			Policies
			BJ	TJ	HB	BJ	TJ	HB	
Industrial process	Oil depot	STAGE I	100	100	30	100	100	100	**Tianjin:** Finish vapor recovery of oil depots and oil stations before the end of 2014. Promote vapor recovery of oil exploration and oil terminals. **Hebei:** Finish vapor recovery of 7,202 oil stations, 82 oil depots and 1,500 tank trucks before the end of 2014. Promote vapor recovery of oil terminals.
	Oil station	STAGE II	100	100	30	100	100	100	
	Crude oil production	STAGE I	0	0	0	0	50	0	
	Crude oil handle	EOP	0	0	0	60	20	20	**Beijing:** Promote comprehensive treatment of VOCs in petrochemical industry and chemical industry. Implement "leak detection and repair" technological transformation of Yanshan Petrochemical Company. Crude oil loss rate should be controlled at 0.3 percent in 2016. **Tianjin:** Promote comprehensive treatment of VOCs in key industries (petrochemical, chemical, pharmaceutical, paint, plastic products, packaging, and printing industries) before the end of 2016. Promote leak detection and repair, online monitoring technology in the petrochemical, chemical and other key enterprises. **Hebei:** Promote comprehensive treatment of VOCs in key industries (petrochemical, chemical, paint, packaging and printing industries). Carry out "Leak Detection and Repair" technical transformation in the petrochemical industry.
	Oil refinery	EOP	0	0	0	60	20	20	
	Chemical industry	EOP	0	0	0	30	30	30	
	Varnish Paint Production	Substitution	0	0	0	50	50	50	**Action Plan:** Promote the use of water-based paint; encourage the production, sale and use of low toxicity, low volatile solvents.
Solvent use	New car varnish paint	Substitution	0	0	0	70	0	0	**Beijing:** Increase the use of low volatile paints, and the proportion of use should be larger than 80% in new car varnish painting projects and larger than 50% in furniture manufacturing and other painting projects. Packaging and printing industry must use inks that meet the environmental requirements. **Tianjin:** Promote comprehensive treatment of VOCs in key industries (petrochemical, chemical, pharmaceutical, paint, plastic products, packaging and printing industry) before the end of 2016. **Hebei:** Promote comprehensive treatment of VOCs in key industries (petrochemical, chemical, paint, packaging and printing industry).
	Wood furniture	Substitution	0	0	0	50	0	0	
	Other industry paint	Substitution	0	0	0	50	50	50	
	Printing ink	Substitution	0	0	0	100	50	50	
	Pharmaceutical Production		0	0	0	0	30	0	

Table 8 Regional end-of-pipe control parameterization scheme (Unit: %): mobile sources

Technology	Control technology	2012			2017			Policies
		Beijing	Tianjin	Hebei	Beijing	Tianjin	Hebei	
Light duty gasoline bus	≤Euro2	8	18	18	0	0	0	Accelerate implementation of fuel and emission standards: implement Euro5 vehicle standards in 2015 for the whole region; implement Euro6 vehicle standards in 2016 for Beijing. Scrap the yellow-labeled and old vehicles: scrap 2 million yellow label vehicles in the region before 2017.
	Euro3	10	40	40	0	11	5	
	Euro4	82	42	42	28	34	37	
	Euro5	0	0	0	43	55	57	
	Euro6	0	0	0	29	0	0	
Light duty gasoline truck	≤Euro2	6	17	17	0	0	0	
	Euro3	11	45	45	0	13	9	
	Euro4	83	38	38	27	34	33	
	Euro5	0	0	0	38	53	58	
	Euro6	0	0	0	35	0	0	
Heavy duty diesel truck	≤Euro2	7	15	15	0	0	0	
	Euro3	93	85	85	35	40	36	
	Euro4	0	0	0	11	13	13	
	Euro5	0	0	0	23	47	51	
	Euro6	0	0	0	30	0	0	
Heavy duty diesel bus	≤Euro2	9	20	20	0	0	0	
	Euro3	91	80	80	12	27	21	
	Euro4	0	0	0	11	15	15	
	Euro5	0	0	0	34	58	64	
	Euro6	0	0	0	42	0	0	
Light duty diesel truck	≤Euro2	6	17	17	0	0	0	
	Euro3	11	83	83	25	32	27	
	Euro4	83	0	0	11	14	14	
	Euro5	0	0	0	28	54	59	
	Euro6	0	0	0	36	0	0	

Notes: the penetrations of vehicle emission standards were calculated based on oil consumption here.
CYC, cyclone dust collector; WET, wet scrubber; ESP, electrostatic precipitator; ESP2, high efficiency electrostatic precipitator; FAB, fabric filters; FGD, flue gas desulfurization; LNB, low NOx combustion technology; SCR, selective catalytic reduction; SNCR, selective non-catalytic reduction; ≤Euro2, include no control and Euro1 and Euro2 vehicle standards; Euro3-6, Euro3-Euro6 vehicle standards; Stage I, Stage I vapor recovery systems; Stage II, Stage II vapor recovery systems; EOP, end-of-pipe technology for VOC; Substitution, substitution with environment-friendly paints and solvents.

Table 9 Control measures in the Action Plan and their emission reductions (Unit: 10kt)

Policies	Sector	Pollutant	Emission reduction		
			Beijing	Tianjin	Hebei
Energy structure adjustment	Power	SO_2	0.69	0.53	-1.74
		NO_X	1.40	-1.50	-2.98
		$PM_{2.5}$	0.23	0.03	-0.84
	Heating	SO_2	2.22	1.35	2.45
		NO_X	1.43	1.32	1.82
		$PM_{2.5}$	0.87	0.21	0.50
	Industrial boilers	SO_2	1.38	1.24	14.88
		NO_X	0.28	0.78	8.38
		$PM_{2.5}$	0.10	0.07	0.48
	Urban residential	SO_2	0.94	0.13	2.75
		NO_X	0.07	-0.05	0.31
		$PM_{2.5}$	0.28	0.05	0.56
	Rural residential	SO_2	0.70	0.12	1.39
		NO_X	0.03	0.04	0.12
		$PM_{2.5}$	0.81	0.34	1.54
Industrial structure adjustment	Industrial process				
Control capacities of steel industry		$PM_{2.5}$	0.00	0.19	0.50
Control capacities of cement industry		NO_X	0.68	0.22	3.56
		$PM_{2.5}$	0.04	0.15	3.15
End-of-pipe reduction					
Desulfurization in coal-fired power plants	Power	SO_2	0.00	3.02	13.73
Denitration in coal-fired power plants		NO_X	0.00	4.93	22.50
Upgrade dust collectors in power sector		$PM_{2.5}$	0.00	0.45	1.30
Denitration in NG power plants		NO_X	0.39	0.00	0.00
Denitration in coal-fired heating plants	Heating	NO_X	0.50	0.00	0.00
Desulfurization in industrial boilers	Industrial boilers	SO_2	0.65	5.07	7.01
Upgrade dust collectors in industrial boilers		$PM_{2.5}$	0.02	0.38	2.05
Denitration in cement industry	Industrial process	NO_X	0.26	0.16	3.61
Desulfurization in sinter plants		SO_2	0.00	1.24	10.25
Upgrade dust collectors in industrial kilns		$PM_{2.5}$	0.59	0.31	3.17
Upgrade dust collectors in steel industry		$PM_{2.5}$	0.00	1.17	6.23
Reductions from vehicles	Transportation	NO_X	5.24	1.40	5.14
		VOCs	2.58	1.69	6.26
		$PM_{2.5}$	0.23	0.07	0.53
VOC reduction					
Control VOC emissions from key industries	Industrial process	VOCs	0.80	2.27	0.85
Vapor recovery	Industrial process	VOCs	4.53	3.63	3.39
Promote environment-friendly paints and solvents	Solvent use	VOCs	2.53	1.70	3.63
Total (emission change in 2017)		SO_2	6.73	13.44	46.15
		NO_X	10.29	7.27	42.37
		$PM_{2.5}$	3.16	3.72	20.87
		VOCs	5.39	0.72	7.13

Table 10 Enhanced control measures emission reductions (Unit: 10kt)

Provinces	Enhanced control measures	Pollutant	Enhanced emission reduction
Hebei	Further cut steel production to ensure reduction of coal consumption increases to 60 million tons rather than 40 million tons.	SO_2/ NO_X/ $PM_{2.5}$	1.00/12.00/2.45
Hebei	Install high efficiency PM control technology for steel industry (ESP and FAB).	$PM_{2.5}$	1.43
Hebei	Install FAB in cement plants.	$PM_{2.5}$	2.26
Hebei	Upgrade dust collectors in coke industry.	$PM_{2.5}$	2.28
Hebei	Diesel vehicles in use should be equipped with DPF.	$PM_{2.5}$	0.34
Hebei	Install denitration facilities in coal-fired heating plants.	NO_X	3.1
Hebei	Install SNCR in all precalcining cement kilns.	NO_X	2.5
Hebei	Industrial coal should be washed, and forbid the usage of high-sulfur coal (sulfur content high than 0.6%).	SO_2	16.4
Hebei	Implement vehicle limit line for diesel vehicles at Euro3 stage in Hebei and Tianjin, and reduce 80% oil consumption by heavy duty diesel vehicles.	NO_X/VOCs	3.04/0.52
Hebei	Reduce VOC emissions from key industries by 30%-40% (coke, paint, and pharmaceutical industry).	VOCs	21.9
Hebei	Increase the proportion of intensive livestock production by 30%, and promote the application of slow-release fertilizers.	NH_3	10.70
Tianjin	Install high efficiency PM control technology for steel industry (ESP and FAB).	$PM_{2.5}$	0.44
Tianjin	Install FAB in cement plants.	$PM_{2.5}$	0.15
Tianjin	Diesel vehicles in use should be equipped with DPF.	$PM_{2.5}$	0.04
Tianjin	Install denitration facilities in coal-fired heating plants (the installing proportion reach 50%).	NO_X	3.45
Tianjin	Implement vehicle limit line for diesel vehicles at Euro3 stage in Hebei and Tianjin, and reduce oil consumption by heavy duty diesel vehicles by 80%.	NO_X/VOCs	0.43/0.08
Tianjin	Industrial coal should be washed, and forbid the use of high-sulfur coal (sulfur content high than 0.6%).	SO_2	0.54
Tianjin	Reduce VOC emissions from key industries by 30%-40% (paint, and pharmaceutical industry).	VOCs	5.60
Tianjin	Increase the proportion of intensive livestock production to 30%, and promote the application of slow-release fertilizers.	NH_3	0.82

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Clean Air Alliance of China (CAAC) , initiated by 10 key Chinese academic and technical institutions in clean air field, aims at providing an integrated clean air collaboration platform in China for academic and technical institutions, provences and cities, Non-profit organizations and enterprises. The overarching goal is to improve air quality in China and mitigate the negative impacts on public health due to air pollution. The members of CAAC include academic institutions, provinces & cities, as well as other nonprofit organizations and enterprises that care about clean air.

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