

Climate Change and Air Quality— Measures with Co-Benefits in CHINA

**Controls aimed at
reducing greenhouse-gas
emissions also decrease
air pollution.**

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Although the Kyoto Protocol is an important step, its impact on global warming, seen in isolation, will be small. Broader participation and deeper cuts in greenhouse-gas (GHG) emissions are essential for any post-Kyoto agreement to have a significant effect. Particularly important are the prospects for curbing GHG emissions in large developing countries, such as China and India, whose CO₂ emissions are projected to grow dramatically over the next few decades. Here we focus on China, which is second only to the U.S. in CO₂ emissions (although the per capita emissions are less than one-sixth of those of the U.S.) and which is expected to become the largest single emitter of GHGs in the coming decades. Several studies carried out in China over the past 5–10 years, including our own work, have found that many measures aimed primarily at reducing local air pollution decrease GHG emissions as a co-benefit. Conversely, a range of CO₂-mitigating policies entail reductions in air pollution as a co-benefit. This implies that the real costs of climate policies in China may be lower than anticipated by the government. In this article, we describe the links between climate change and air-quality issues as well as the health and environmental benefits accruing from alternative measures and policies for CO₂ mitigation in China. We argue that the tremendous potential to cut GHG emissions while simultaneously reducing air pollution should make cooperation on climate-control strategies more attractive to China and other countries in a similar position.



The blessings and curses of coal

Since ancient times, people in northeastern China have been using coal for sculpting (see the photo of a coal sculpture from Taiyuan on p 4824); the history of coal carving can be traced back 6000–7000 years. Probably in about the third century B.C., the Chinese became the first to start burning coal. Around the 11th century A.D., the Chinese figured out how to use coal to produce coke, which became a substitute for charcoal in metallurgy (1). At that time, deforestation around the blast furnaces had become acute because of the use of charcoal, which is produced from wood. In its attempt to solve one environmental problem, however, the country created a range of others, as the demand for coal grew steadily over the following centuries.

Around 1990, more than three-quarters of China's energy consumption came from coal. In the past few decades, the share of coal in the country's total energy consumption has been slowly decreasing. However, economic growth is still largely fueled by coal, which constituted 69% of total commercial energy consumption in 2004. After a temporary dip in coal consumption during 1998–2000, consumption more than doubled in the period 2000–2004, from 455 million tons of oil equivalent (Mtoe) in 2000 to 957 Mtoe in 2004 (2). The growth is especially pronounced for production of electricity and heat

in power plants. In 2004 alone, China was building power plants at a rate of one large (1000-MW) power plant per week (3). Coal-fired power plants now produce 47% of China's CO₂ emissions (4). China has large coal reserves, and the country will probably continue to rely on them for many years to come. Reducing the emissions of GHGs and air pollutants associated with the use of coal—for instance, by improving energy efficiency and cleaning the emissions—thus seems crucial to reduce detrimental environmental effects of a continued economic growth in China.

In China and other developing countries, reducing GHGs is not high on the political agenda, although improving energy efficiency and reducing environmental damage are (see the box on p 4825). An impressive improvement in energy efficiency and a corresponding reduction in the CO₂ intensity of the economy have been seen in China over the past few decades (Figure 1), although investment in energy conservation projects has weakened in recent years (3). Considerable potential exists for reducing GHGs just by appealing to increasing energy efficiency and reducing environmental effects. Here we summarize some of the main findings from studies that look at measures and policies with a potential for mitigating both GHG emissions and air pollution, subsequently referred to as “co-control”, in China.

Costs and benefits

The studies described below take a variety of approaches to estimating costs and benefits of projects and policies that reduce emissions. A detailed bottom-up analysis is often used to evaluate the costs and benefits of concrete abatement options in a single city. Transport models, often with an atmospheric chemistry module to allow for formation of secondary pollutants, are used as a first step to



NATIONAL MUSEUM OF COAL (TAIYUAN, SHANXI)

Coal sculpture from Taiyuan.

model how identified emission sources cause population exposure and how emission reductions may decrease exposure. The next step is to combine the exposure data with so-called exposure-response (or concentration-response) functions (the quantified relationship between health risk and exposure to air pollution) and data for the actual frequency in the given area of, for example, deaths and hospital admissions due to air-pollution-related diseases. The output is an estimate of the number of cases that can be attributed to air pollution and to what extent these numbers may be reduced as a re-

welfare parameters. These are particularly suitable for assessing the impacts of national-level policies, such as a CO₂ tax. Typically, top-down modeling involves a more simplified representation of the links between economic activities and the environmental damage they cause. Middle-ground approaches include energy-sector and scenario-based methods that combine exogenous economic or energy-sector scenarios with more or less generic technology options.

Knowledge about the relationships between exposure, effect, and valuation is essential for all the methods described above. As detailed for some cases later, large uncertainties often exist. However, as discussed by Rabl et al., a cost-benefit analysis may give very useful information, even if the uncertainties are large (5).

Climate-change and air-pollution links

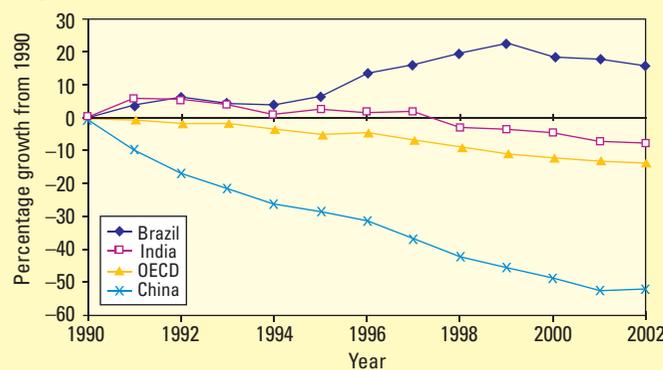
Climate-change and air-quality issues are linked in several ways. First and foremost, the main GHG CO₂ and the main air pollutants to a large extent stem from the same sources. For a range of control initiatives, targeting these common sources thus typically implies abatement of both CO₂ and air pollutants. Several previous studies in both developing and developed countries have demonstrated that the near- to medium-term co-benefits of CO₂-abatement policies, which primarily consist of reduced damage to human health from air-quality improvements, can offset a large fraction of the mitigation costs and even exceed the costs significantly in some cases (6–14). Whereas the climate impact of long-lived GHGs is independent of the source location, the adverse impacts of air pollution are directly related to the location and height of emissions and their proximity to people, forests, crops, structures, and other assets that can be damaged from air-pollution exposure. Long-range transport of air pollution may affect recipients far away from emissions sources. Acid rain and SO₂ pollution affect soil and vegetation over large areas in China (15). And the atmospheric lifetimes for ozone and fine particulate matter (particles with diam <2.5 μm; PM_{2.5}) are long enough to survive transport from one region to another, causing pollution-related damage in both. The health and environmental benefits resulting from co-control of CO₂ and air pollution will thus depend on the site-specific characteristics of the area where emissions cuts are implemented and the areas to which the pollution is transported. Few, if any, studies have attempted to fully account for co-benefits of CO₂ abatement in a regional context. Several studies, however, point to regional air pollution and resulting impacts on agriculture and people as an increasing problem in China (16–19).

In addition to the source linkage between climate-change and air-quality issues, increasing evidence exists that well-known air pollutants, especially tropospheric ozone and particles, play an important role in the climate system (20, 21). Air pollutants may affect climate in different ways. Tropospheric ozone, for which NO_x, volatile organic compounds (VOCs), and carbon monoxide (CO) are important precursors, is a GHG and thus has a warming ef-

FIGURE 1

CO₂ intensity of the economies of different countries and regions in 1990–2002

CO₂ intensity is the amount of CO₂ emitted per unit of GDP (measured in purchasing power parity in international dollars). OECD: Organisation for Economic Co-operation and Development. Adapted from Ref. 4.



sult of emissions abatement. Impacts on agricultural crops and materials can be estimated in a similar fashion. If a price is added to the units of damage outcome, the environmental economic costs can be estimated, as well as the benefits of reducing the emissions. Alternative abatement options can then be ranked according to their costs and benefits.

Top-down approaches use a macroeconomic model to estimate the impacts of introducing a given abatement measure on the whole economy and on

fect on the atmosphere. Particles have either a cooling effect on the atmosphere through scattering of shortwave radiation (sulfate and organic carbon particles) or a warming effect through absorption of shortwave radiation (black carbon particles). In addition to the direct effects of scattering or absorption, particles may indirectly influence climate by affecting clouds and the albedo of snow and sea ice. The various effects that particles have on the atmosphere and clouds in a region may result in regional climate changes. For instance, Menon et al. suggest that the observed trend toward increased summer floods in southern China and drought in the north may be linked to absorbing particles that alter the regional atmospheric circulation and contribute to regional climate change (22).

Finally, climate change and air quality are linked through the chemistry of the atmosphere, as some air pollutants influence the lifetimes of GHGs. The hydroxyl radical, OH, plays a major role in atmospheric chemistry, because it is the primary oxidant in the atmosphere. For example, it reacts with CO and methane in the troposphere. Thus, increases in CO emissions will contribute to lowering the OH concentration, which, in turn, will tend to increase the methane concentration.

Co-control of CO₂ and air pollution: Case studies in Shanxi

Our studies of a range of options for energy efficiency and clean coal technology in Shanxi province indicate that potentially large combined benefits exist related to air-quality and human-health improvements, energy savings, and CO₂ control.

Shanxi lies in the central part of northern China and is one of the country's major energy bases, with rich coal and iron deposits. Taiyuan, its capital, was classified in 1999 as the most polluted city in China. About two-thirds of the city's industrial gross domestic product (GDP) is generated by heavy industries, partly state-owned enterprises with outdated technology. Moreover, industrialization in rural areas has increased coal consumption in town and village enterprises, resulting in large emissions encircling the city. Finally, Taiyuan's pollution problems are exacerbated by its location in a basin, which enhances the concentrations of pollutants.

Air quality in Taiyuan, as in many other larger cities in China, has improved in recent years because of numerous government actions. For in-

stance, whereas the annual average SO₂ level was ~280 µg/m³ in 1998, it decreased to ~80 µg/m³ in 2004. PM is also steadily decreasing, although levels are still rather high, with PM₁₀ concentrations of ~165 µg/m³ in 2004. The World Health Organization gives 20 µg/m³ as a guideline for the maximum rec-

Air quality and health in China

China's first ambient-air-quality standards were issued in 1982. Since then, various environmental laws and regulations have been implemented. Examples are the SO₂ Pollution Control Zones, instituted in 1998; the Law on Energy Conservation legislation, approved in 1997; the Total Emission Control policy, approved in 2000; and the Cleaner Production Law, instituted in 2002. In 2005, a law promoting renewable energy was passed, and the Chinese government recently made a decision to decrease CO₂ emissions unilaterally by reducing the energy intensity 20% over the next 5 years. Energy intensity is also introduced as one of several indicators by which the National Development and Reform Commission evaluates cities' environmental performance. In spite of somewhat weak enforcement throughout the years, environmental laws and regulations have resulted in improved air quality in many Chinese cities over the past few decades. On average (for ~130 larger cities across the country), SO₂ concentrations have decreased steadily, and the annual average is now <50 µg/m³, which is the maximum level previously recommended by the World Health Organization (WHO). In its updated air-quality guidelines (23), WHO suggests that an annual guideline is not needed, because compliance with the 24-h guideline level (20 µg/m³) will ensure low values for the annual level in many cities (38). This decrease is occurring even though total SO₂ emissions are increasing (15). Particulate matter (PM) pollution has improved in many cities in the past couple of decades, although it has worsened in some. However, in contrast to the SO₂ trend, PM concentrations leveled off, and then the average for the 130 cities began to increase again in the period 2000–2002 (Figure 3; 38). On average, for the same cities, annual NO₂ levels have been stable at ~30–35 µg/m³ for the past 2 decades, slightly below the maximum level of 40 µg/m³ recommended in the WHO guideline. However, the rapid increase in car ownership is expected to result in increasing NO_x levels.

WHO has quantified the health risks of a range of major risk factors and estimates that ~300,000 premature deaths in China per year can be attributed to urban ambient air pollution (39). Health impact assessments for air pollution use the results of epidemiological studies that provide exposure–response functions. Relatively few epidemiological studies of air-pollution effects have been carried out in China compared with Western countries. Aunan and Pan reviewed Chinese air-pollution epidemiology and, with some exceptions, found that Chinese studies report somewhat lower exposure–response coefficients than studies in Europe and the U.S. (40).

An important issue in health-damage assessment is the long-term impact of air pollution on death rates, which is likely to exceed by far the day-to-day impacts captured by short-term time-series studies. Typically, long-term cohort studies, which compare death rates over time among populations living in different areas with varying pollution levels, report exposure–response coefficients that are an order of magnitude larger than those reported in short-term time-series studies. Unfortunately, no long-term studies have been carried out in China or other comparable countries. Until such studies are available, exposure–response functions from Western countries need to be transferred and adjusted to China and other developing countries, as WHO did in its global assessment (the large U.S. cohort study by Pope et al. [41] was adjusted and applied). Although this introduces uncertainties, the alternative would be to leave out the long-term impact, and that would almost certainly lead to a severe underestimation of the effect.

ommended annual mean PM₁₀ concentration (23). The EU guideline is 40 µg/m³ (24), whereas the U.S. national ambient-air-quality standard is 50 µg/m³ (25). Levels of NO_x are increasing because of the increased influence of transport. Other large cities in Shanxi, such as Datong in the north and Yuncheng

FIGURE 2

Estimated annual number of deaths avoided because of CO₂-mitigation options

The upper measures marked T (for Taiyuan) and S (for Shanxi) are the ones given in Table 1. Adapted from Ref. 28.

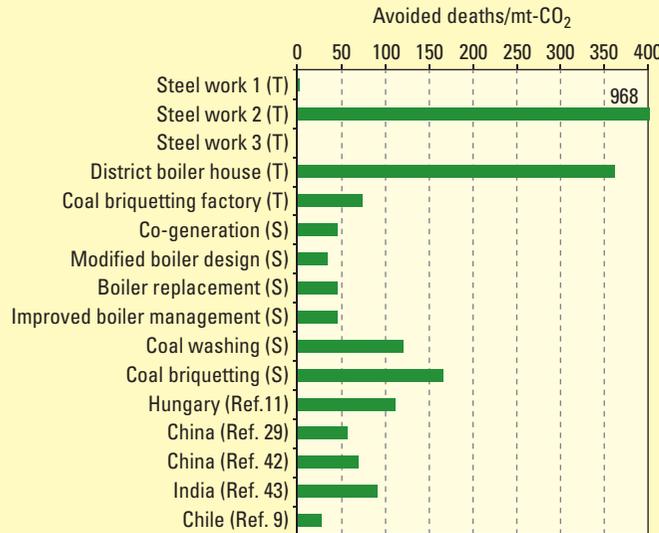
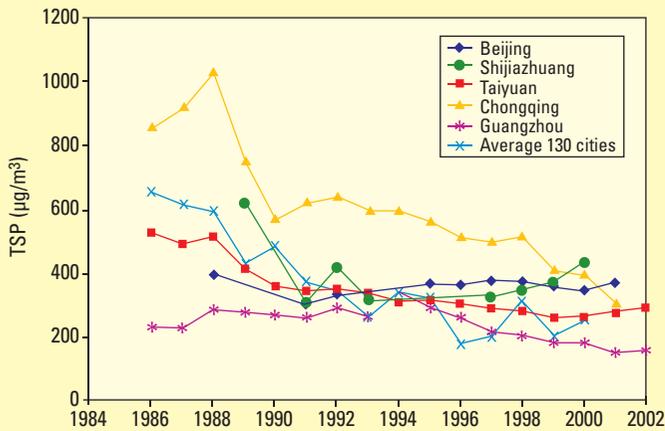


FIGURE 3

Annual average levels of total suspended particles (TSP) in selected Chinese cities and the average for 130 major cities, 1986–2002

Adapted from Ref. 38.



in the south, have received less attention than the capital and have not seen the same reduction in PM and SO₂ levels.

Policy options that can potentially mitigate both CO₂ and air pollution from coal use in Shanxi in general and Taiyuan in particular include coal washing; coal briquetting; co-generation of heat and electricity; a range of energy-saving and clean-coal options at the large iron and steel plant located within the residential/commercial areas in Taiyuan (with ~65,000 employees and 54 stacks at different heights); expanded district heating; and replace-

ment, improved management, or modified design of small industrial boilers (for details, see 13, 14, and 26). Shanxi has many such boilers, and until recently, the capital alone had ~3000. Industrial boilers and furnaces in general consume almost half of China's coal and are the largest single type of point sources of urban air pollution (27).

As shown in Table 1, several of the selected measures are financially profitable, with saved energy costs resulting in negative abatement costs even before any health and environmental benefits are taken into account. The individual potentials of these options to reduce CO₂ and provide health benefits (via air-pollution reductions) vary considerably, however. This implies that the ranking of abatement options according to their unit cost (per ton CO₂, when they are regarded as potential GHG options) is substantially altered when local health benefits are considered. For example, coal briquetting and coal washing seem to be among the most expensive options for reducing emissions of CO₂, but they provide large local benefits. One important reason why electricity-saving projects, for instance, show the smallest co-benefit per ton CO₂ reduction is the fact that they reduce emissions through high stacks at power plants. These emissions affect local air quality only to a very limited extent, but as discussed previously, they may have significant regional impacts. From a local perspective, without accounting for the regional effects on health and environment caused by the emissions, the measured health co-benefits of CO₂ abatement necessarily will be largest for abatement of low-emission sources. Figure 2 provides estimates of the annual number of avoided deaths per 1000 t CO₂ reduction as a consequence of mitigation options in China and other countries. The estimates refer to the short-term impact of PM₁₀ pollution on mortality rates. Short-term impacts probably constitute only a limited share of the actual impact related to premature deaths from air-pollution exposure (see the box on p 4825).

Typically, the estimated co-benefits of CO₂ mitigation are higher in regions where emissions of air pollutants are not abated, or only abated to a limited extent. It should also be noted that many simple measures to reduce air pollutants, such as baghouses or electrostatic precipitators at coal-fired power plants, will decrease efficiency and thus increase GHG emissions. The highest and lowest estimates of co-benefits of CO₂ mitigation shown in Figure 2 are from detailed bottom-up assessments in which local features of emissions, dispersion, and population densities are allowed to influence the results. Of course, the denominator—how effectively the measure reduces CO₂—is also important for the values. For a comprehensive picture of a measure's potential for combined GHG and air-pollution reductions to be obtained, information like that given in Table 1 is needed.

Potential CDM projects?

Detailed information like that in Table 1 is also useful when evaluating potential Clean Development Mechanism (CDM) projects. CDM, one of the flexibility mechanisms of the Kyoto Protocol, allows industrial

countries to help meet their targets by investing in projects in developing countries that will reduce GHG emissions below a business-as-usual baseline. Energy-savings and clean-coal projects are often mentioned as potential CDM projects. By some accounts, China is home to half of the world's CDM potential. In an assessment of domestic benefits from exploiting China's energy-related CDM potential, Vennemo et al. synthesize a significant body of recent research on co-benefits of climate abatement in China (mostly bottom-up studies but some top-down) and estimate that 34–161 lives are saved for each million tons of CO₂ reduced in China (28). This implies that CDM projects can potentially save ~3000–40,000 lives every year. Additional gains related to reduced damage to agricultural crops and materials were estimated to reach ≥1 billion Chinese yuan annually. It can be argued that these benefits ensure that the projects “contribute to sustainable development”—a requirement for CDM projects, according to the Kyoto agreement.

Taxing CO₂ saves lives and crops

An economy-wide climate policy is likely to take the form of a carbon tax or a tradable carbon credit scheme. In China, mandated energy efficiency is also a possibility. Before committing to a climate or energy policy, decision makers would presum-

ably like insight into how the policy would affect the overall national economy, GDP growth, and the different economic sectors. Only a macroeconomic model can provide this insight. The message from the study by Aunan et al. is clear: Policy makers in China have nothing to fear from implementing a CO₂ tax (29). The environmental benefits associated with the air-pollution reductions that accompany fuel switching and with the changes in energy efficiency that result from the implementation of a CO₂ tax more than offset the costs to society, at least up to CO₂-abatement levels of 10–20%. Approximately half of the offset is from public-health improvements. The other half is related to crop loss avoided because of reduced levels of surface ozone. The study by Aunan et al. is the only study we know of that attempts to quantify the regional impacts on surface ozone and resulting crop damage from CO₂-abatement policies (29).

Indoor air pollution: Synergies with climate-change mitigation?

Most of the studies of health co-benefits of CO₂-abatement and CDM projects in China focus on ambient air pollution. However, indoor air pollution due to dirty household fuels is most likely responsible for a larger death toll in China (~420,000

TABLE 1

Options for reducing emissions of CO₂ and air pollutants in Shanxi: Annual costs and benefits

The affected population in Taiyuan is 2.07 million, and the affected population in Shanxi is 16.24 million. Adapted from Refs. 13 and 14.

Option	Abatement cost (\$/t-CO ₂)	CO ₂ reduction (Mt)	Health benefit (million \$)	Net benefit (million \$)	Net benefit/CO ₂ reduction (million \$/Mt) ^a
<i>Taiyuan</i>					
Iron and steel 1 (coke dry quenching)	119.7	0.02	0.0	-2.1	-118.2
Iron and steel 2 (electrical arc furnace)	247.9	0.03	19.0	12.3	459.2
Iron and steel 3 (combined-cycle power production)	-52.5	0.53	0.1	27.7	52.7
Iron and steel 4 (top gas-pressure recovery turbine)	-45.6	0.05	0.0	2.1	45.6
District boiler house	37.1	0.05	12.7	10.9	228.1
Coal briquetting factory	1.7	0.24	12.9	12.5	52.2
<i>Shanxi</i>					
Co-generation	-30	0.32	10.3	19.9	62.3
Modified boiler design	-6.2	12.80	305.1	384.5	30.0
Boiler replacement	-2.7	12.32	401.7	434.9	35.3
Improved boiler management	9.2	3.70	119.9	85.8	23.2
Coal washing	22.7	11.81	1030.9	762.8	64.6
Coal briquetting	27.3	6.78	816.7	631.6	93.2

^aAnnual abatement cost per CO₂ reduction minus annual health benefit per CO₂ reduction.

annually) than ambient urban air pollution is (30). This is because >70% of the Chinese population still depends on solid fuels, mostly in rural or peri-urban areas and less-developed cities and towns. Burning of solid fuels in household stoves leads to large emissions of health-damaging products of incomplete combustion, including particles (PM_{2.5}) (see the photo of a simple portable coal stove below). High levels of indoor air pollution lead to high rates of acute and chronic respiratory diseases, including lung cancer (30, 31).

Emissions from dirty household fuels may also play an important role in global warming, especially through black carbon particles (mainly soot), as described above. Streets and Aunan estimate that combustion of coal and biofuels in Chinese households has contributed 10–15% of the total global emissions during the past 2 decades (32). How the Chinese household sector develops during the next 50 years will have an important bearing on future particle concentrations. Household energy development is likely to be closely associated with economic growth and development in rural areas (33). The case for targeting black-carbon emissions in a global-warming context is not yet clear, however, as reductions in black carbon will typically be accompanied by reductions in other components, such as organic carbon, sulfate-containing particles, and surface ozone precursors (34). As described above, these have diverse impacts on climate, on both global and regional scales.



Simple coal stoves are still used in many Chinese households.

Prospects for future GHG abatement in China

China is among the developing countries that are likely to be put under heavy pressure to take on obligations post-2012, when the present Kyoto Protocol expires. However, climate change is not currently a high priority in China. On the other hand, China is seeking access to energy-efficient and clean technologies and is interested in getting funding through CDM. For the time being, China is considered an increasingly more interesting supplier of CDM projects. This seems to have been an incentive for Chinese participation in negotiations on mitigation of climate change. The country is also engaging in initiatives that focus on technology development and

Emissions related to coal use

Coal burning leads to emissions of a range of greenhouse gases (GHGs) and air pollutants. They include

- CO₂, the most important GHG;
- SO₂, which damages health, materials, and vegetation and is the main precursor of acid rain;
- NO_x (= NO + NO₂), which contributes to ground-level ozone and is a precursor of acid rain;
- CO, which has adverse health effects;
- hydrocarbons (methane, an important GHG; and other volatile organic compounds, which contribute to ozone formation);
- mercury, which has adverse health effects; and
- particles, which contain metals, elemental and organic carbon, and sulfur and nitrogen compounds; they cause serious health problems and affect climate.

Emissions of air pollutants from coal burning may vary considerably according to the coal quality and combustion conditions. This implies that coal burning can have very different impacts on human health and the environment depending on what kind of coal is used and the combustion technology applied.

transfer and are at the same time geared toward GHG mitigation (e.g. the Asia-Pacific Partnership on Clean Development and Climate [35] and the China-EU Partnership on Climate Change [36]). In a workshop in Beijing in November 2005 (37), climate policy makers, advisers, and researchers within the fields of air pollution and climate change from across China and elsewhere discussed the synergies and trade-offs between the policy areas of air pollution and climate change. Although the political rhetoric still implies no opening up of the possibility of post-Kyoto climate commitments, there are signs that Chinese policy makers are starting to recognize the large potential for benefits through co-control of air pollution and CO₂. An indication of this is that SEPA is beginning to engage in activities that focus on the co-benefits of air pollution and GHG abatement policies.

Perhaps the largest obstacle to a more proactive Chinese climate policy domestically and at the international level is that until now, it has been treated as a foreign-policy issue. The result is fragmentation. Climate policy remains an international issue handled by the national government, whereas policy issues that are potentially very important for the future of GHG emissions remain within the domestic sphere and are handled independently from climate-change policy issues. If government agencies at the national and provincial levels engaged in environmental protection, urban and rural energy issues, transport, and industrial development, for example, have a larger say in how climate policy is formulated, this picture may change. Increased concern that energy security and local and regional air pollution are threatening continued economic growth and people's welfare may in the end turn out to be decisive for how China chooses to address its contribution to global warming.

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