Health Impact and Control Policy of Air Pollution in Shanxi, China

Dissertation for the degree of Philosophiae Doctor (Ph. D.)

By

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Daisheng Zhang

Oslo, May 2013

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Paper II: Daisheng Zhang, Kristin Aunan, Hans Martin Seip and Haakon Vennemo, 2011. The energy intensity target in China's 11th Five-Year Plan period—Local implementation and achievements in Shanxi Province. Energy Policy 39: 4115–4124.

Paper III: Daisheng Zhang, Kristin Aunan, Hans Martin Seip, Thorjørn Larssen, Haakon Vennemo, Steinar Larssen, Liulei Feng, Caixia Wu and Ruikai Xie, 2012. Air Pollution reduction during China's 11th Five-Year Plan period - Local implementation and achievements in Shanxi province. Environmental Development 4: 36–53.

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Abbreviations and Acronyms

BAU: Business-As-Usual

BP: British Petroleum

CCICED: The China Council for International Cooperation on Environment and Development

COI: Cost of Illness

CVD: Cardiovascular Disease

DPSIR: Driving Forces-Pressures-State-Impacts-Responses

EEA: European Environment Agency

EPB: Environment Protection Bureau, China

FGD: Flue Gas Desulfurization

FYP: Five-Year Plan

GDP: Gross Domestic Product

HC: Human Capital

MEP: The Ministry of Environmental Protection, China

Mt: Million tonnes

NBS: National Bureau of Statistics, China

NEC: National Emission Ceilings for certain pollutants

NILU: Norwegian Institute for Air Research

OECD: Organisation for Economic Co-operation and Development

PM: Particulate Matter

PM_{10}: particles less than 10μm in aerodynamic diameter

$PM_{2.5}$: particles less than 2.5μm in aerodynamic diameter

PWE: Population Weighted Exposure

RDP: Regional Domestic Product

RMB: Ren Min Bi (Chinese Yuan)

RR: Relative Risks

S1: Control Scenario 1

S2: Control Scenario 2

SBS: Shanxi Bureau of Statistics, China

SIA: Secondary Inorganic Aerosol

SOE: State of Environment

TCE: Tonnes of Coal Equivalent

TEC: Total Emission Control

TSP: Total Suspended Particles

VOLY: Value of a Life Year

VSL: Value of Statistical Life

WHO: World Health Organization

WTP: Willingness to Pay

YOLL: Years of Life Lost

Abstract

Facing the increasing environmental degradation locally and globally, the Chinese government sets mandatory goals of 10% reduction of SO_2 emission and 20% reduction of energy intensity in its 11^{th} Five-Year Plan period (FYP, 2006-2010). This study uses Shanxi Province to show the health effects of air pollution and health benefits resulting from various air pollution control scenarios in Shanxi province, illustrate how policies and measures have been implemented in practice in the province as a response to the National Environmental Five Year Plan issued by the central government, and demonstrate how the various responses have contributed to meeting targets.

The study shows that the economic costs of air pollution in Taiyuan in the base year 2000 were large, and that control strategies especially targeting area sources (low level distributed sources) could lead to substantial health benefits for the population in Taiyuan and that the gain is greater the earlier control actions are taken. The results in Paper I have been updated, using exposure-response functions from the most recent publications on the topic. Although there are large uncertainties in the estimates of health benefits and the implementation of air pollution control measures, the study shows that scenario-based and pollution source-oriented health benefit evaluation of air pollution in Taiyuan can be very useful. Even though selection of optimal control scenarios for Taiyuan requires further cost-benefit analysis and regional considerations, this study does provide decision-makers with evidence about not only the significance of control and prevention of environmental pollution, but also gives indications of what measures are most effective locally. The national air quality standard Grade II is a bit less strict than the WHO guidelines, and the study implies that there are large health benefits to be gained by setting stricter standards for the future in China. China has already in 2012 set a new ambient air quality

standard which lowers the previous threshold value of PM_{10} (Grade II: annual average from 100 $\mu g/m^3$ to 70 $\mu g/m^3$) and includes an index (standard) for $PM_{2.5}$ (Grade II: annual average 35 $\mu g/m^3$) for the first time.

The achievements in energy saving and emission reduction in Shanxi have been substantial in the 11^{th} five-year plan period (2006-2010). The provincial and local governments have put energy efficiency and environment protection very high on its policy agenda, and devoted a considerable amount of effort to achieving the goals. Very detailed requirements and regulations have been issued. The most important measures so far seem to be in the industrial sector. Particularly, the Top-200 Program and phasing out outdated capacity contributed, respectively, 63% and 30% of the total energy savings. The reduction by FGD in the power sector dominated the total SO_2 reduction.

However, Shanxi has still a long way to go to achieve satisfactory energy use and limit the emissions of pollutants such as SO_2, NO_x, CO_2 and PM. Further improvement of energy intensity and environment will require continuing efforts to optimize the economic structure, in particular a shift to low-carbon economy and reduction in the dependence on heavy industry. The personnel appraisal system should also be improved to provide stronger incentives for achieving further energy intensity and pollution reductions.

1. INTRODUCTION

1.1 General introduction

Since 1978, when the opening and reform policy was initiated, China has managed to sustain an average growth rate of 9.9% with an aggregate GDP reaching ¥51.9 trillion in 2012 (National Bureau of Statistics (NBS), 2012 and 2013). Not surprisingly, the massive economic expansion has induced a substantial increase in energy consumption. China's total energy consumption reached 3.6 billion tonnes of coal equivalents (TCE) in 2012, with an annual growth rate of 5.7% since 1978. Consequently, China has surpassed the USA and become the world's largest consumer of energy products. China accounted for 71% of global energy consumption growth in 2011 (BP, 2012).

The energy structure dominated by coal and the rapid growth of polluting industries have resulted in great impacts and pressures on the environment, which have caused considerable international and domestic concerns (Gan, 1998; Economy, 2007; Vennemo et al, 2009). The World Bank (2007) estimated that the economic burden of air and water pollution in China was between 362 and 781billion RMB Yuan in 2003, or 2.7 - 5.6 percent of GDP. According to the World Health Organization, about 0.8 million premature deaths worldwide each year can be attributed to the effects of urban outdoor air pollution, of which about 300 000 occur in China (Cohen et al., 2004, Zhang and Smith, 2007). In the comparative risk assessment under the Global Burden of Disease 2010 study estimates for the impact of air pollution in China (and globally) are considerably higher. The estimated number of annual premature deaths in China due to ambient air pollution in 2010 is 1.23 million, whereas an estimated 1.04 million premature deaths were attributable to household air pollution (indoor and neighborhood $PM_{2.5}$ pollution from use of traditional household fuels)[1].

China's CO_2 emissions have increased dramatically, according to BP (2012) from about 1.4 billion tonnes in 1978 to 9.0 billion tonnes in 2011 (26.4% of global emissions), and overtook USA (which emitted 6.0 billion tonnes in 2011) as the world's largest emitter of energy-related CO_2 in 2006. Other sources give somewhat different values. Guan et al. (2012) compared emissions obtained from various sources and methods. They found for instance that in 2010 the emissions obtained by summing the values for all provinces in China were 1.4 billion tonnes larger than the given national value.

The national and international impacts from air pollution and greenhouse gas emissions in China have been a major concern to the Chinese policy makers. In order to improve the situation, China incorporated, for the first time in its 11th Five-Year Plan, mandatory goals for energy saving and pollution reduction and this is widely considered an important step towards building a "harmonious society" through "scientific development". However, there was general agreement that it would be impossible to achieve the new goals without strong involvement of provincial and local governments. The problem was how local authorities would contribute, considering that, in China, environmental efforts have lacked effectiveness, resulting in an implementation gap, and that the biggest obstacles to environmental policy implementation are at the local level (OECD, 2006). Previously, Chinese economic development oriented promotion incentives ensured a strong motivation of local government officials to maintain the rapid development of local economy (Zhou, 2004; Li and Zhou, 2005), ignoring environmental costs.

[1] Country estimates can be extracted from Institute for Health Metrics and Evaluation (IHME), 2013. Global Burden of Disease (GBD) Visualizations http://viz.healthmetricsandevaluation.org/gbd-compare/.

1.2 General objective of the study

Health damage from air pollution due to energy consumption is a major concern worldwide. Fossil fuels, the primary source of energy, are the largest source of ambient air pollution in urban areas, producing, for instance, sulfur- and nitrogen oxides, dust, soot, and other suspended particulate matter. These pollutants can lead to serious public health problems, including acute and chronic respiratory illnesses like pneumonia and chronic bronchitis, and may lead to premature death for the more vulnerable (Kampa and Castanas, 2008).

The objective of this thesis is to estimate the health effects of various air pollution control scenarios in Shanxi province, describe how policies and measures have been implemented in practice in the province as a response to the National Environmental Five Year Plan issued by the central government, and assess how the various responses have contributed to meeting targets.

Paper I estimates the health damage from air pollution in 2000 in Taiyuan, the capital of Shanxi Province, and assesses to what extent identified options for energy efficiency improvements and air pollution reduction were likely to improve population health in various scenarios. The actual pollution situation in 2005 was compared to the scenarios.

Paper II and III illustrate how environmental policies and measures were implemented in practice at a local scale as a response to the National FYPs issued by the central government. Paper II focused on energy efficiency improvement and Paper III on air pollution reduction.

2. Materials and Methods

2.1 Health impact of air pollution

Pollution can cause damages to people, goods, and nature. However, the damages are quite often not fully accounted for by the polluter. Thus, from the polluter's viewpoint, the damages are external. As defined by Heck and Hirschberg (2011), an impact on a group of persons or on the environment, which is caused by another group but which is not fully accounted for by the causing group, is called an externality. Harmful externalities are called ‘external costs’.

Many studies on external costs associated with air pollution have been undertaken in recent years. Various frameworks for comparative assessment of health and environmental impacts have been developed and implemented in different settings. One of the most detailed methods for environmental impact and external cost modeling is the so-called “impact pathway approach” developed under the ExternE Project, a research project of the European Commission[2]. The impact pathway approach allows the impacts from emission sources within specific energy chains to be estimated. The analysis steps involve quantification of burdens (e.g., emissions), calculation of changes of pollutant concentrations, quantification of impacts on receptors like humans, animals, and crops, and, if of interest, economic valuation. Figure 1 shows the basic steps of the impact pathway approach.

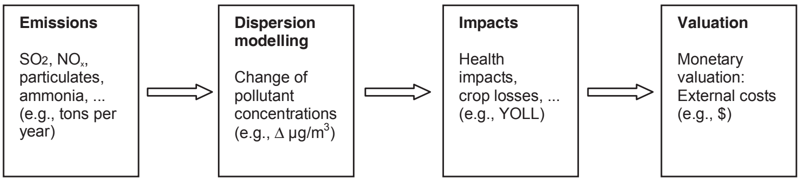


Fig. 1. Environmental impact assessment: The impact pathway approach. (YOLL is years of life lost.)
Source: (Heck and Hirschberg, 2011).

The DPSIR framework[3] (Driving Forces-Pressures-State-Impacts-Responses), which is used by European Environment Agency (EEA), is another similar approach but includes policy impacts and response. It is used to assess and manage environmental problems. Driving forces are the

[2] http://www.externe.info/externe_d7/?q=node/46 .
[3] http://root-devel.ew.eea.europa.eu/ia2dec/knowledge_base/Frameworks/doc101182 .

socio-economic and socio-cultural forces driving human activities, which increase or mitigate pressures on the environment. Pressures are the stresses that human activities place on the environment. State, or state of the environment, is the condition of the environment. Impacts are the effects of environmental degradation. Responses refer to the responses by society to the environmental situation.

Emissions

Particulate matter (PM), SO_2, NO_x, O_3, greenhouse gases, several organic pollutants, metals and semimetals with potential human or environmental toxicity are the most important air emissions considered in impact assessments. Currently, inhalable particles (particles less than 10μm in aerodynamic diameter, or PM_{10}), fine particles (particles less than 2.5μm in aerodynamic diameter, or $PM_{2.5}$), SO_2 and nitrogen dioxides (NO_2) are the criteria pollutants in China and are routinely monitored in most Chinese cities.

- Particulate matter (PM), also known as particle pollution (also PM), is a complex mixture of extremely small particles and liquid droplets. Particle pollution is made up of a number of components, including acids and salts (such as nitrates and sulfates), organic chemicals, metals, and soil or dust particles. Several epidemiological studies have found evidence of health damages due to inhalable particulates in the air (Dockery et al, 1993; Pope et al, 2002; 2009; 2011). Their potential for causing health problems is directly linked to the size of particles. There is evidence that the fine fraction $PM_{2.5}$ (particulates with diameter up to 2.5μm) is associated with greater risks than larger particles. **Primary particles** are directly released into the atmosphere by wind, combustion processes, or human activities. **Secondary particles** are those that form in the atmosphere from other gaseous pollutants, particularly sulfur dioxide, nitrogen oxides, ammonia, and volatile organic compounds. Secondary particulates are typically in the fine fraction and are assumed to cause similar health impacts as primary particulates. Particulates interfere with solar radiation, affect cloud formation and brightness, may affect surface albedo, and thus influence climate (Heck and Hirschberg, 2011; WHO, 2011).

- Sulfur dioxide (SO_2). Current scientific evidence links SO_2 with a variety of environmental damages, particularly on human health, ecosystems, crops, and building materials (Eliasson and Lee, 2003). SO_2 can cause direct economic impacts by affecting crop yields. Acidification resulting from SO_2 emissions is hazardous to natural ecosystems. Further, the formation of sulfates (secondary particulates) in the atmosphere imposes more serious health impacts than SO_2 itself. Sulfates also have influence on the climate (Heck and Hirschberg, 2011; WHO, 2011).
- Nitrogen oxides (NO_x). Associations between NO_x, and daily mortality or respiratory hospital admissions in several Chinese and European cities have been reported (Cao et al., 2011; Chang et al., 2003; Diaz et al., 1999; Kan et al., 2008; Nafstad et al., 2004). As a precursor of nitrates (secondary particulates), NO_x also have effects on climate and plays a role in the chemistry of ground-level ozone, which affects human health, some materials, crops, and natural ecosystems (Heck and Hirschberg, 2011; WHO, 2011).
- Sulfate and nitrate formation in ambient particles. Sulfate in ambient air mainly comes from oxidation of sulfur-containing precursors, among which SO_2 is the largest contributor. SO_2 can be oxidized to H_2SO_4 by gas-, aqueous- or multi-phase reactions with OH, H_2O_2 or O_3, followed by condensation or nucleation of H_2SO_4 both onto pre-existing particles and new particles with partial or full neutralization by NH_3. It is first

partially neutralized as NH_4HSO_4 (see reaction 1), which may be further neutralized as $(NH_4)_2SO_4$ (see reaction 2). Sulfate is often found in the fine mode (<1 μm) in atmosphere.

$$NH_3+H_2SO_4 \rightarrow NH_4HSO_4 \quad (1)$$

$$NH_3+NH_4HSO_4 \rightarrow (NH_4)_2SO_4 \quad (2)$$

Nitrate particulate is formed by homogeneous gas-phase oxidation of nitrogen oxides to gaseous nitric acid, which may be followed by reaction with gaseous ammonia to form highly volatile NH_4NO_3 (see reaction 3). Like sulfate, nitrate is normally distributed in the fine mode in the form of ammonium nitrate.

$$NH_3+HNO_3 \rightarrow NH_4NO_3 \quad (3)$$

Sulfate, nitrate and ammonium (usually referred to as SIA, secondary inorganic aerosol, secondary since they are formed in the atmosphere from their precursors) are the predominant inorganic components of fine particulate matter with diameters less than 2.5 μm ($PM_{2.5}$), making up approximately half of total $PM_{2.5}$ mass (Querol et al., 2004; Pinder and Adams, 2007; Tsimpidi and Karydis, 2007; Yang et al., 2011). In general, H_2SO_4 and HNO_3 are neutralized mainly by NH_3. $(NH_4)_2SO_4$ is more stable, but NH_4NO_3 is formed if excess NH_3 is available beyond the sulfate requirement (Wang et al, 2013).

Given the nature of studies on health impact of air pollution, it is difficult to disentangle the effects of each pollutant. As a result, individual pollutants such as $PM_{2.5}$, PM_{10}, SO_2, NO_2, CO or

O_3 are often used as an indicator of air pollution in epidemiological studies. As these pollutants mostly originate from energy use, their concentrations are often correlated. O_3 is a possible exception because of its non-linear relationship with precursor gases. Thus adding the impacts of all pollutants would potentially overestimate the contribution of air pollution to the increase in mortality and morbidity (Kunzli, 2002). In this study (Paper I), PM (PM_{10}) was selected as a surrogate pollutant in estimating the overall health impacts because it is believed that PM is responsible for the largest fraction of mortality attributable to air pollution exposure.

Dispersion Modelling

Some studies of China's air pollution use measured PM concentrations that include primary and secondary particulates. The advantage of such studies is that they are using directly measured data and can give a picture of the pollution situation as a whole in the monitored areas. The disadvantage of studies using only data from measurements is that they are based only on point measurements, which may not be representative, and, often do not identify the sources of pollution.

By contrast, the advantage of detailed modeling from emission sources to damages is that the polluting sources can be identified and the associated damages can be quantified. The detailed models help to advise decision makers which emission reductions are most effective.

The dispersion model used in this study (Paper I) to simulate ambient concentrations of pollutants under different control scenarios is AirQUIS, the state of the art air quality management tool developed by Norwegian Institute for Air Research (NILU) (http://www.nilu.no/airquis/). AirQUIS uses emissions, meteorology and topography as input and simulates hourly ambient concentrations (see Paper I for details).

Impacts

The impacts are usually quantified by use of exposure–response functions. Exposure–response functions for human health are estimated based on epidemiological studies (Dockery et al, 1993; Pope et al, 2002; 2009; 2011). A number of air pollution health studies have been conducted in China since 1990s, which include changes in all cause mortality and of cardiopulmonary disease, and morbidity, as well as number of out-patients and emergency room visits (Cao et al., 2011; Chang et al., 2003; Kan et al., 2008). The relationships between air pollution and respiratory and other clinical symptoms, lung functions and immune functions have also been assessed. Generally, short-term exposure studies (time-series, case cross-over or panel studies) capture the acute effects of air pollution by examining the association between daily mortality (or morbidity) and daily or multi-day changes in air pollution, while long-term exposure studies (cohort, cross-sectional or ecological studies)[4] reveal that long-term exposure to air pollution might lead to an increased risk of health hazards in the population (Aschengrau and Seage, 2013).

Aunan and Pan (2004) conducted a meta-analysis of studies associating PM_{10} exposure and health response in China, and their results were used in Paper I of this study. Meanwhile, Pope et al (2002, 2011 and 2012) studied lung cancer and cardiopulmonary mortality and long-term exposure to fine particulate air pollution in the USA. The studies by Pope et al. are considered to be the most reliable basis for the assessment of chronic mortality effects from air pollution because of the long follow- up period, the large sample size, and the broad consideration of possibly confounding effects like smoking. Since Chinese studies of long-term impacts on mortality were not available at that time, the results of Pope et al. were used in the current study

[4] Study Designs Commonly Used in Epidemiologic Air Pollution Studies. http://www.healtheffects.org/Asia/papasan-design.htm.

(Paper I) to calculate mortality effects (exposure-response functions for $PM_{2.5}$ were used directly for PM_{10}).

The question arises whether the exposure–response model derived from the studies by Pope et al. can be transferred to China, where characteristics of outdoor air pollution and socio-demographic status of local residents are different from those in the United States. In an ecological cross-sectional study in Shenyang (Wang et al., 2003), an increased cardiovascular mortality risk of about 0.67% per $\mu g/m^3$ $PM_{2.5}$ increment was found. It is close to the findings of the studies by Pope et al. Because both the cross-sectional and ecologic designs have important limitations that make them less scientifically rigorous than cohort studies (Aschengrau and Seage, 2013), and considering Chinese cohort studies were not available, it was considered warranted to assume that exposure– response functions derived from the studies of Pope et al. could also be applied to China where the air pollution level is often very high. This question is discussed further in the Discussion section in the light of new results.

Valuation

Monetization is a suitable method for aggregating health impacts and environmental burdens, putting different physical units into a single damage indicator. An economic assessment is convenient when comparing the costs and benefits of abatement measures, technological choices, or policy regulations. To obtain the damage costs, one multiplies the impact (e.g., the number of hospital admissions) by the cost per case (US$ per hospital admission). Regarding damage to marketable goods like crop losses or material damages, the monetary valuation is relatively straightforward by using market prices though a large crop loss is likely to affect prices or induce a switch to other crops, an effect not accounted for in most studies. The monetary valuation is conceptually more difficult for nonmarket goods like human health damages. For health impacts, the unit costs include the cost of illness (COI), wage- and productivity losses, which are market-based factors, as well as nonmarket costs that take into account an individual's willingness to pay (WTP) to avoid the risk of pain, suffering, and premature death. WTP estimates may be obtained, e.g., by asking individuals how much money they are willing to spend to achieve a benefit, or may be based on how much one has to pay people to take risky jobs.

To estimate the cost of avoiding a respiratory or cardiovascular hospital admission, one has to use COI, because there are no available WTP estimates. Analysts often rely on COI estimates as a lower bound to the theoretically correct value of avoiding illness in cases where WTP estimates are not available (The World Bank 2007).

For mortality impacts, either the so-called 'value of a life year' (VOLY) is used to monetize 'years of life lost' (YOLL) or the so-called 'value of statistical life' (VSL) is used to monetize cases of premature death. The monetary valuation of mortality in terms of VSL or VOLY is a controversial issue. In industrialized countries there is wide consensus that the willingness-to-pay (WTP) approach based on individual preferences is more appropriate than the so-called human capital (HC) approach, which is solely based on an individual's wage losses plus interest earnings (i.e. individual income), due to accidental death (Heck and Hirschberg, 2011).

The HC approach, which has often been used in China, uses the gross domestic product (GDP) per capita to value a life year lost. According to experiences from WTP studies, the WTP-based VSL is usually in the order of 50–200 times the GDP per capita of the country (Guo and Hammitt, 2009; Aunan et al, 2004; Heck and Hirschberg, 2011). Therefore, WTP-based studies usually result in much higher monetary values for health damages than HC-based studies.

Heck and Hirschberg (2011) pointed out that there is another controversial issue, which is the use of different WTP VSL figures for different regions of the world: a lower WTP VSL (or a lower VOLY) does not imply a lower valuation of life. Rather the seriousness of losses of other opportunities, associated with the spending of a certain amount of money (say 100 US$) to reduce a particular risk, is usually higher for an average person in low-income countries than in high-income countries. Consequently, the willingness to pay for the reduction of a certain environmental risk (which is only one risk among many) is usually lower in low-income countries than in high-income countries.

2.2 Control policies on air pollution and their evaluation

Program or policy evaluation is typically undertaken periodically to investigate how a program develops and to what extent policies or other program activities give the expected results. Evaluations of a program can provide recommendations to make adjustments and identify lessons learned for the design of future programs.

A recent evaluation of the 11th Five Year Plan by Yuan et al (2011) focused on policy evolution and progress of energy conservation and pollution reduction in China during the 11th FYP periods, and based its assessment on energy saving and pollution reduction data and policy reviews. The evaluation methodology involved describing the situation before the 11th FYP, outlining the key objectives in the 11th FYP, and evaluating the progress related to quantitative objectives, indicators, policies, and reforms at national, provincial and key field levels. Then lessons from the 11th FYP periods were drawn and policy suggestions were proposed for long-term successful implementation of energy conservation and pollution reduction in China.

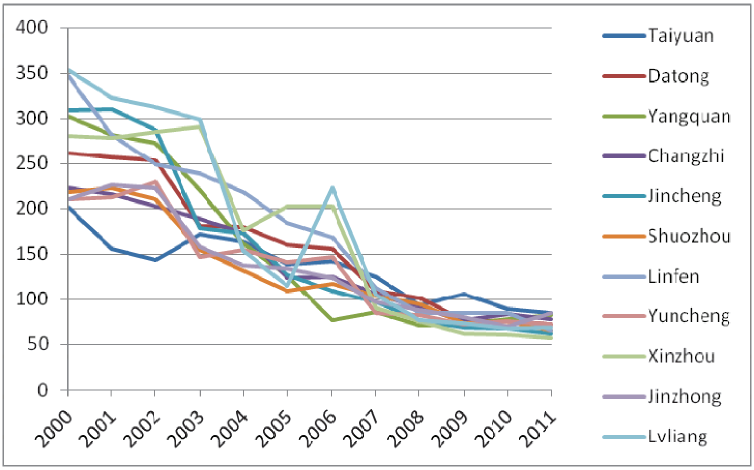
The current study (Papers II &III) followed a similar approach. The evaluations of targets for energy intensity and SO_2 reduction in the 11th Five Year were conducted as follows. Regarding the evaluation of the target for energy intensity (Paper II), energy conservation prior to 11th FYP was reviewed; next, the key objective in the 11th FYP was outlined and the overall plans, actions and policies for achieving it were detailed; then a quantitative assessment was made for the overall energy savings attributed to the 11th FYP during the 2006-2009 (2010) period based on two alternative assumptions, see Paper II. Further, a number of individual programs or policies were evaluated in more detail to assess their overall achievements as well as to determine whether they were meeting their stated goals; and finally, lessons from the 11th FYP periods were drawn and policy suggestions were proposed for long-term successful implementation of energy conservation in Shanxi. As for pollution reduction, the approach adopted was similar to that used for the energy intensity. To estimate the effects of the provincial programs, we in this study estimated baseline SO_2 emissions for the period 2006-2010, assuming no change in the SO_2 emission cleaning situation after 2005. In order to disentangle the emission reductions from some major SO_2 reducing policy measures so as to understand which ones have been the most effective, we estimated emissions reduction from different sources and measures compared to an estimated baseline. The SO_2 emission reduction from electricity generation by flue gas desulfurization (FGD) and by closing down outdated production capacities were estimated, see Paper III.

2.3 Shanxi Province

Shanxi Province, located in northern China, with a population of about 34 million (2.6% of China's total population), is the most important coal base of the country. In 2005, the base year of 11th FYP, Shanxi produced 554 million tonnes (Mt) of coal, which is about one fourth of the national total; 129 billion kWh of electricity, 5% of the national total; and 80 Mt of coke, more than one third of the national total (NBS, 2006).

Since 1978, the start of opening and reform process in China, Shanxi's economy has been growing very fast with an 11% annual regional domestic product (RDP) growth rate till 2012. The rapid growth and the low efficiency of energy consumption pose great pressure on the environment. During the 10th FYP period, Shanxi was the most polluted province and home to the 3 most polluted cities in China for three consecutive years (2003-2005) according to the ranking of the air pollution index of 113 key cities under national surveillance of environmental protection (MEP, 2003-2005).

a



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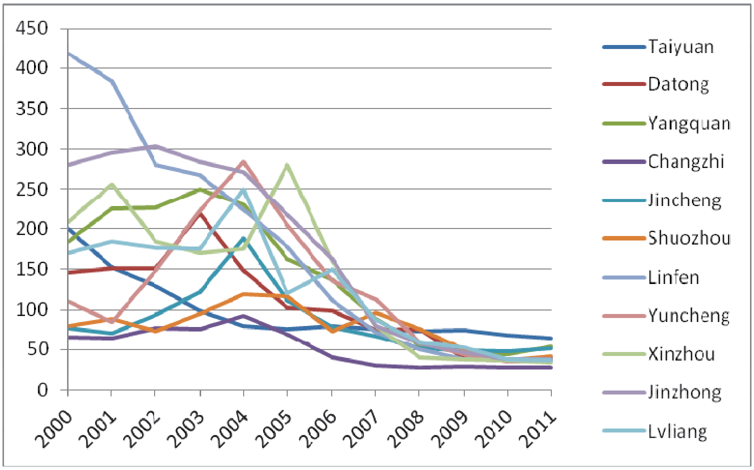

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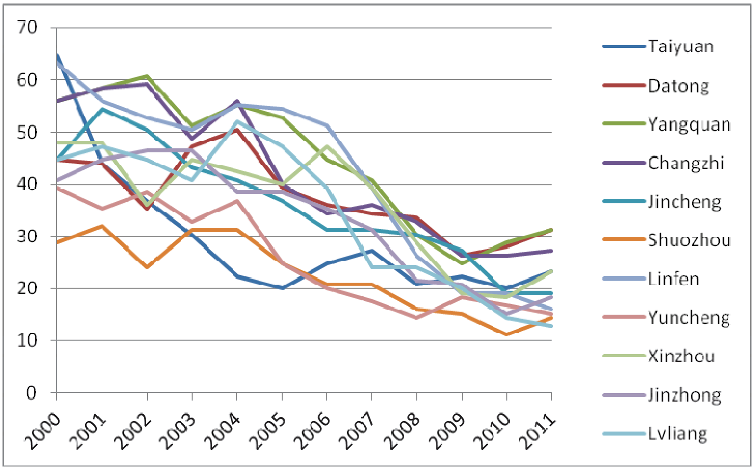

Fig. 2. SO_2, PM_{10} and NO_2 concentration in 11 key cities of Shanxi (μg/m^3): (a) PM_{10} concentration, (b) SO_2 concentration, (c) NO_2 concentration.
Source: SOE of Shanxi 2000-2011 (Shanxi EPB, 2001-2012)

According to Shanxi EPB (2012), considerable improvements have been made in air quality in Shanxi since the beginning of the 11th FYP. None of the 11 key cities satisfied grade II requirements in 2005, while 10 did so in 2011. The last one, Taiyuan, reached grade III.

Compared to 2005, in Shanxi, the annual average concentration of PM_{10} had in 2011 decreased by 49% and that of SO_2 and NO_2 had decreased by 72% and by 45%, respectively (Shanxi EPB, 2012) (see Fig. 2).

Taiyuan

Taiyuan, with more than 3 million urban populations in 2010, is the capital of Shanxi. Taiyuan is located in the middle reaches of the Yellow River in North China and is surrounded by hills to the west, north and east. The rapidly developing economy of Taiyuan is largely propelled by massive coal consumption. The total energy consumption of Taiyuan in 2000, the base year of the current study (Paper I), amounted to 41.83 million tonnes of coal equivalent (NBS, 2001) and its energy intensity in 2006 was 2.4 times the national average (NBS, 2007). Heavy reliance on coal combustion as a source of heat and power has created serious environmental problems in Taiyuan. Due to the topography, air pollution in Taiyuan easily becomes severe. PM and sulfur dioxide (SO_2) are the major pollutants of concern.

In 2000, the annual average TSP concentration was 401 $\mu g/m^3$, 2 times as much as the upper limit of national air quality standard grade II (200 $\mu g/m^3$), and 11 times of that of WHO guideline (PM_{10}: 20 $\mu g/m^3$ annual mean) assuming a PM_{10}/TSP conversion factor of about 0.55 (Aunan et al., 2004). The daily average ranged from 66 to 2493 $\mu g/m^3$ TSP. During heating season, the daily average was 448 $\mu g/m^3$, 1.21 times as much as the level during non-heating season, 369 $\mu g/m^3$, and 4.9 times as much as that of WHO guideline (PM_{10}: 50 $\mu g/m^3$ 24-hour mean) (WHO, 2005). Xie et al. (2006) reported elevated concentrations of certain trace elements, particularly arsenic and selenium in PM_{10} sampled in March 2004 in Taiyuan. As-concentrations ranged from 12 to 83 ng/m^3, with the arithmetic average of 43 ng/m^3, far exceeding the WHO guidelines for Europe (WHO, 2001), which is 0.7 ng/m^3. Arsenic is one of the most toxic trace elements. Arsenic and selenium have long been recognized as coal combustion markers. Xie et al. (2006) reported that high correlations of Al and Se with PM_{10} signified coal combustion as a dominant source of particulate pollution in Taiyuan.

In 2000, the annual average of SO_2 concentration was 200 µg/m^3, 2.33 times as much as the upper limit of national air quality standard grade II (60 µg/m^3). The daily average ranged from 14 to 1090 µg/m^3. During heating season, the daily average was 350 µg/m^3, 3.65 times higher than during non-heating season (96 µg/m^3), and 17.5 times higher than the World Health Organization (WHO) guidelines (20 µg/m^3 for 24-hour mean) (WHO, 2005).

Considerable improvements have been made in energy saving and air quality in Taiyuan since 2000. According to SBS (2011) and Shanxi EPB (2012), the energy intensity decreased 36% during 11th FYP in Taiyuan from 2.67 tce/10000RMB in 2005 to 1.71 tce/10000RMB in 2010, and the annual average concentration of PM_{10}, had by 2011 decreased by 58% and that of SO_2 and NO_2 had decreased by 68% and by 65%, respectively, compared to 2000 (Shanxi EPB, 2012) (see Fig. 1).

3. Main results and findings

3.1 Health impact of air pollution in Taiyuan

Paper I considered the pollution situation in Taiyuan in 2000 and scenarios for 2010, and 2015. In order to assess to what extent the identified options for energy efficiency improvements and air pollution reduction had improved or were likely to improve population health in Taiyuan, four pollution scenarios were considered:

- Baseline 2010: business-as-usual (BAU). The BAU scenario towards 2010 was based on projections in the 10th five-year plan for Shanxi province;
- Control scenario 1(S1): Use of natural gas and coal-bed methane to replace coal gas in households and in the public sector and substitute coal burning in medium and low stack height industrial pollution sources (stack <30m);
- Control scenario 2 (S2): District heating replacing household heating stoves and inefficient small-scale boilers , and
- Grade II attainment scenario for 2015: This study assumed that the air quality in Taiyuan on average will reach National Standard Grade II in 2015, i.e. the annual daily average of TSP<200 $\mu g/m^3$ (PM_{10}<100 $\mu g/m^3$).

The AirQUIS model was used to estimate PM_{10} reduction for the four options in a study region, which is a 24km×40km area of the inner city of Taiyuan with grid cells 1km×1km and covered most of the urban areas and the main point sources for particulates and SO_2. A comprehensive emissions inventory built for the project "Master Plan against Air Pollution in Shanxi" (NORAD CHN0040 Project Report, 2005) was used and the model was calibrated according to the measured air quality for both TSP and SO_2. The estimated air quality was in good agreement with the observed pollution levels in 2004 in Taiyuan.

The estimated air pollution reduction was combined with population density in order to calculate reduction in Population Weighted Exposure (ΔPWE). The ΔPWE was then combined with dose-response functions for several health end points. A unit price for the different health end points were given and economic benefit (social cost) of the projects was estimated.

The mean total economic cost of health effects associated with ambient air pollution in urban areas of Taiyuan in 2000 was estimated to about 1.7 billion Yuan ($210 million, 1$=8.26 Yuan, exchange rate in the year 2000 used hereafter), using WTP estimates. This is 4.9% of the total RDP in Taiyuan (6.2% of the urban area RDP which is about 80% of the total). If the adjusted human capital approach was used assuming an 11% RDP growth rate the cost is about 800 million Yuan ($100 million) which was 2.4% of the total RDP (3.0% of the urban area RDP). Assuming a 6% RDP growth rate – a quite conservative estimate – gives 480 million Yuan or $60 million which is 1.4% of the total RDP (1.8% of the urban area RDP). Like in many other studies, the economic costs associated with long-term health effects dominated the total in this study: 98% of the total using WTP approach and 89% using the HC approach. The economic cost of chronic bronchitis was about 110 million Yuan ($13 million) if WTP approach was used and about 60 million Yuan ($7 million) if HC approach was used (at 11% RDP growth rate), respectively.

Under BAU scenarios, mean total economic cost of health effects associated with ambient air pollution in urban areas of Taiyuan in 2010 was estimated to about 6.3 billion Yuan ($760 million) if WTP estimates were used, which is 3.7 times the estimate for 2000. If the adjusted human capital approach was used this study arrived at about 3.6 billion Yuan ($440 million) for BAU 2010, which is 4.5 times that of 2000 with 11% RDP growth rate, or 2.1 billion Yuan ($250 million) with 6% RDP growth rate.

The health benefits for different scenarios were also estimated. The monetized health benefit is estimated at about 490 million Yuan ($60 million) in 2010 under S1 (the natural gas utilization scenario), 2.7 billion Yuan ($330 million) under S2 (district heating scenario) if the WTP approach is used, and 280 million Yuan ($34 million) under S1 and 1.6 billion Yuan ($200 million) under S2 if the HC approach used, which are 7.7% and 44% of the economic cost of the 2010 BAU, respectively.

In fact, during the 10^{th} and 11^{th} FYP (2000-2010), not only the above two scenarios but a series of comprehensive policies, as will be discussed later, have been implemented for improving air quality in Taiyuan. Using data on observed air quality for 2010, the monetized health benefit was estimated at about 4.8 billion Yuan ($585 million) if the WTP approach is used, and 2.8 billion Yuan ($334 million) if the HC approach used, which are 77% of the economic cost of the 2010 BAU and 1.5 times the health benefits of the sum of S1 and S2.

The results also indicate that even if TSP (PM_{10}) reaches the national standard II (200μg/m^3 of TSP and 100 μg/m^3 of PM_{10}) in 2015, the economic cost of health effects of particulate air pollution in urban areas of Taiyuan will still be considerable, about 6 billion Yuan ($700 million) if the WTP approach is used and about 2.7 billion Yuan ($300 million) if the HC approach is used, which are about 2.1% and 0.9% of predicted RDP in 2015.

The implications of new exposure-response functions on effects of measures to reduce emissions are described in the Discussion section.

3.2 Control policies

It is clear from the results of Paper I that the control options would have improved the health status significantly for Taiyuan residents had they been implemented. Actually, as will be discussed later, many comprehensive control policies including the options studied in Paper I, have been implemented during the 11^{th} FYP. This is contrary to what has been perceived to be the case in previous FYPs. Generally, the perception is that environmental efforts have lacked effectiveness in China, resulting in an implementation gap, and studies have shown that the biggest obstacles to environmental policy implementation often are at the local level (OECD, 2006). The current study used Shanxi province as a case to illustrate how policies and measures were implemented in practice at a local scale as a response to the National FYPs issued by the central government. The illustration is from two aspects: energy conservation (Paper II) and air pollution reduction (Paper III).

3.2.1 Energy conservation policies

Based on a review of energy policies, this study found that the actions taken in Shanxi to reach the energy saving target (i.e., reduction in the energy intensity of the economy) mainly fall into four categories: enhancing energy management, economic restructuring, technical renovation and transformation, and supplementary policies. The estimates show that Shanxi contributed nearly 5.6% of the total national energy savings and that the lion's share of the energy savings in Shanxi in the period 2006-2009 was due to energy intensity improvements in the industrial sector. According to reported energy savings, the Top-200 Program contributed 63% of the total energy savings, and according to our estimates phasing out outdated capacity contributed 30%. Meanwhile, through implementation of key projects and actions targeting the population in general, achievements in energy conservation in the social fields, which includes primary industry, tertiary industry, residential sector and the construction sector (part of the secondary industry), were also significant and contributed 7% of the total reported achievements.

3.2.2 Air pollution reduction policies

In order to meet the pollution reduction goals, a series of policies and measures were implemented during the 11^{th} FYP period. The actions taken in Shanxi to reach the pollution reduction targets can roughly be summarized into four categories: pollution control engineering ('end-of-pipe' measures and process modifications), economic restructuring, enhancing environmental management, and supplementary policies. The energy conservation policies are part of this package. The current study shows that the reduction from the power sector contributed the lion's share of the estimated total SO_2 emission reduction in the first four years of the 11th FYP in Shanxi. The reduction by FGD dominated the total reduction. Other measures include reduction of SO_2 emissions from existing production capacities in other industrial sectors than the power sector, and in the domestic sectors, e.g. closing down small-to-medium boilers through expanding the coverage of district heating supply and replacing domestic coal use for heating and cooking by expanding the coverage of coal gas supply. The SO_2 emission reduction from closing down outdated production units is rather low consistent with the fact that the estimated coal used in these closed down production units only accounted for 4% of the total reported coal consumption during 2006-2009.

4. Discussion

Paper I of this thesis indicate that the economic cost of air pollution related to health damage in Taiyuan is huge, 1.7 billion Yuan ($210 million), about 4.9% of its RDP (6.2% of the urban RDP) in the base year 2000 if the WTP approach is used. This is close to 6.9% reported recently for China for the same year, decreasing to 5.9 % for 2005 (Matus et al., 2012) and agrees with the review by Heck and Hirschberg (2011) which finds that estimates of the external costs of air pollution in China range from approximately 1% to 8% of China's GDP.

However, there are many sources of uncertainty in computing health effects attributable to air pollution (see Paper I for details). The adoption of exposure-response functions is a very important one. Especially there are large uncertainties involved in estimating the impact of long-term exposure using studies conducted in developed countries. Up till recently, most studies of long-term health effects of air pollution in China were ecological in nature, thus limiting the power for causal inference. Recently, Cao et al. (2011) conducted a cohort study (the only one we are aware of so far in China) to examine the association between outdoor air pollution and mortality in 70,947 middle-aged men and women in the China National Hypertension Survey and its follow-up study. The baseline survey and follow-up evaluation were conducted in 1991 and 2000. Air pollution exposures, including TSP, SO_2 and NO_x, were estimated by linking fixed-site monitoring data with resident zip code. Associations were found between air pollution levels and mortality from cardiopulmonary diseases and lung cancer. An increase of 10 μg/m^3 of TSP was associated with, respectively, a 0.3% (95%CI: −0.1%, 0.6%), 0.9% (95%CI: 0.3%, 1.5%), 0.3% (95%CI: −0.6%, 1.3%), and 1.1% (95%CI: -0.1%, 2.3%) increase of total mortality, cardiovascular mortality, respiratory mortality and lung cancer mortality, after adjustment for potential confounders including smoking. Compared with air pollution long-term effects studies in developed countries (Pope et al., 2002; Pope and Dockery, 2006), this Chinese cohort study reported much lower effect responses per unit increase of pollutant concentrations. This cohort study strengthens the assumption that lower exposure-response functions may be found in Chinese air pollution studies compared with those conducted in North America and Europe (Aunan and Pan, 2004). More recently, however, Pope et al. (2009) and (2011) have demonstrated that the exposure-response relationship between cardiovascular disease mortality and fine particulate matter is relatively steep at low levels of exposure and flattens out at higher exposures. Similarly, according to The World Bank (2007), some Chinese studies also indicate a slight flattening of the mortality exposure-response function at high concentrations.

Fig. 3 shows a comparison between various exposure-response functions. The ranges of $PM_{2.5}$ concentration covered by studies from China (estimated from TSP) and US are different. The $PM_{2.5}$ range covered by Cao et al. (2011) was 44-195 μg/m^3; Pope et al. 2002 was 11-26 μg/m^3 excluding smoking; Pope et al. (2009) was 0-15,000 μg/m^3 including smoking, and Pope et al. (2011) was 0-30,000 μg/m^3 including smoking. Since the lowest concentration in the study by Cao et al. (2011) was 44 μg/m^3, the shapes of these curves at lower concentrations are not known and the linear extrapolation down to 20 μg/m^3 may not be correct. If there is a large effect at low concentrations as in the US study, the lines in Fig. 3 should actually be shifted along the RR-axis to higher values.

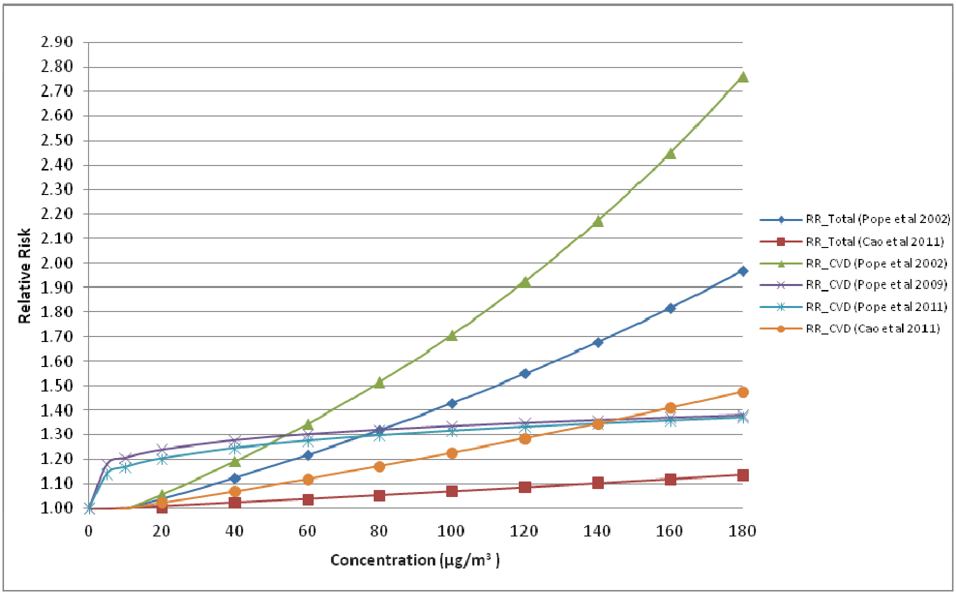

Fig. 3. $PM_{2.5}$ exposure-response functions from the US cohort study (Pope et al., 2002, 2009 and 2011) and the Chinese cohort study (Cao et al., 2011). Note that the lowest TSP concentration in the study by Cao et al. (2011) was 113 μg/m^3 corresponding to about 44 μg/m^3 of $PM_{2.5}$. How these curves behave at the lowest concentrations is therefore not known.

One characteristic of the curves and their comparison is worthy of note. The level of the relative risk (RR) given by the curve determines the total damage in a certain situation, while the steepness of the curve determines the benefit from control strategies that change the concentration level. It is noteworthy that the new CVD-curves from Pope et al. (2009 and 2011) have a higher RR level than the curve from Cao et al. (2011) in a large concentration range (0-140 μg/m^3), assuming that the latter curve is linear until it reaches RR=1.00. The curves from Pope et al. thus give higher total damage, while they are less steep than the Cao curve, resulting in less effect/benefit of interventions.

Applying the exposure-response functions from Cao et al. (2011) implies that the estimated total mortality and CVD mortality attributable to air pollution in the base year 2000 in Taiyuan are only 21% and 43% of the original estimates of this study (in paper I which were based on the functions from Pope et al. (2002)). However, as pointed out above, none of these functions are well suited for estimating attributable cases when the concentration level is below about 40 μg/m^3 $PM_{2.5}$. Applying the nonlinear power functions of the exposure-response relationship between long-term exposure to $PM_{2.5}$ and risk of CVD mortality from Pope et al. (2009) and (2011) results in the CVD mortalities from air pollution in the base year 2000 in Taiyuan being 51% and 49% of the original estimates of this study.

The functions from Cao et al. (2011) are well suited for estimating effects of interventions which will not bring the $PM_{2.5}$ concentrations below about 40 μg/m^3. Fig. 3 shows that in that concentration range, the curve for CVD mortality from Cao et al. (2011) is steeper than those from Pope et al. (2009) and (2011), but less steep than the curve from Pope et al. 2002. For example, health benefit estimate for avoided CVD mortality by control scenario 2 (S2 in Paper I) based on the exposure-response function from Cao et al (2011) is 5 times of that based on Pope et al (2009) and 4 times based on Pope et al (2011), while, 29% of that based on Pope et al (2002).

We conclude that the exposure-response functions from Pope et al. (2002) from US studies that were applied in Paper I, result in considerable overestimation of both attributable cases to air pollution and benefits from interventions, compared to the results obtained when the more recent exposure-response (E-R) relationships are used. According to Pope et al. (2009), the exposure-response functions for different age groups are different (relative risks (RR) associated with cigarette smoking were larger for younger and middle-aged individuals (<65) than for the elderly (≥65)). Thus more long-term epidemiological studies on the exposure-response relationship between long-term exposure to particulate pollution and health impacts covering wider range of $PM_{2.5}$ concentration and in different age groups are urgently needed.

Urbanization and migration also contributes to the uncertainty of the estimated health effects. According to SBS (2011), the population in the urban area of Taiyuan reached 3 million in 2010, which is about two times the prediction of this study based on the natural growth rate. The total number of births was only 176,000 during 2003 to 2010 in Taiyuan. Thus, the results of this study are likely to be underestimates since many places, which previously were rural areas outside the modelling area of the study, have changed to be urban areas due to the urbanization in the past decade.

The health impact study in this thesis shows that control strategies especially targeting all the smaller and medium sized distributed sources with no or low stack heights (called area sources) could lead to substantial health benefits for the population in Taiyuan and that the gain is greater the earlier control actions are taken. Of course, this is from a local perspective. For high-stack emissions the local impact is modest, whereas the regional impact can be substantial (lower concentrations but spread over a larger area). Long-range transportation of SO_2 causes acid rain and sulfates, harming ecosystems and buildings as well as health, and tropospheric ozone formed from long-range transportation of NO_2 and other ozone precursors leads to crop loss (Aunan et al., 2000) and health damage. Long-range transportation of particulates gives elevated concentrations in the ambient air over long distances. Intake fraction studies have shown that the impact of emissions from e.g. power plants increases substantially when increasing the geographic scale of the estimates (Zhou et al., 2003; Wang et al., 2006). This study found that the background concentration in Taiyuan was high and it is believed that a considerable part of the pollution is due to long-range transportation sources outside the model area. Thus, control policies need also to pay attention to higher stack sources, mainly industrial sources.

The total emission control (TEC) policy, the concept of limiting total mass emissions which has been a part of China's environmental toolkit for more than 15 years, was first implemented in 1996 in the Ninth Five Year Plan of China and the Compendium of Long-term Objectives for 2010 (The State Council, 1996). The TEC policy fundamentally changed the approach of controlling pollution in China and it has been the foundation for subsequent environmental policies; more than 15 years after its introduction, China has already witnessed that the 1996 TEC policy and the Ninth Five-Year Plan were mutually reinforcing and aggressive in controlling pollution emissions and the policy has become the most important component of China's pollution control system and will continue to play an important role in the future. A similar approach is also applied in Europe. National Emission Ceilings for certain pollutants (NEC Directive) sets upper limits for each Member State for the total emissions in 2010 of the four pollutants responsible for acidification, eutrophication and ground-level ozone pollution (sulphur dioxide, nitrogen oxides, volatile organic compounds and ammonia)[5], based upon an analytical procedure where emission ceilings are distributed to each country so that the total effect to reduce the damage on the European scale is maximized. The TEC ceilings are determined based upon a simpler (box) calculation, still the principle behind the TEC and NEC are similar. The TEC method misses the important difference between low and high level sources, in terms of their local pollution impact. This important topic in air pollution control is taken into account in the analysis of this thesis (Paper I).

Our study shows that the energy saving and pollution reduction achievements in Shanxi have been substantial in the 11th FYP period. The fact that energy efficiency is very high on the policy agenda of China's governments at all levels, is demonstrated by the variety of policies being implemented. In order to achieve the TEC target set by national 11th FYP, a series of policies have been implemented. In Shanxi, the government's decision to focus on those sectors which yield the greatest immediate impact seems to be the main reason for the achievements.

The CCICED Assessment Report on Pollution Reduction in the 11th Five-year Plan (CCICED, 2011) attributed the progress achieved during 11th FYP in China to several key factors which also apply to Shanxi: maintaining environmental caps, i.e. fixed targets, when economic growth is greater than expected. Pollution abatement projects, i.e. FGD installation, contributed the largest reductions and laid a solid foundation for success. To implement a package of polices to reduce emissions, including some economic incentives such as desulfurized electricity price, and strengthening the accountability and performance of local governments, were the most significant advance in environmental protection in the 11th Five Year Plan.

[5] National Emission Ceilings. http://ec.europa.eu/environment/air/pollutants/ceilings.htm

CCICED (2011) also pointed out that achieving emission reduction targets in the 11th Five Year Plan produced co-benefits. The data available indicate that these achievements have resulted in substantial improvements in environmental quality, saved consumption of 490 million tonnes of standard coal, and reduced carbon dioxide emissions by 1.13 billion tonnes[6].

On March 14, 2011, the Twelfth Five-Year Guideline for National Economic and Social Development was approved at the annual meeting of the National People's Congress, marking the beginning of the 12th FYP period (2011–2015). With the introduction of the 12th FYP, China's leadership established politically-binding targets for energy intensity (16% below 2010 levels), SO_2 (8% below 2010 levels), NO_x (10% below 2010 levels), and CO_2 intensity (17% reduction in emissions per unit of GDP relative to 2010 levels).

Yet some issues that occurred in the 11th Five Year Plan period should be further studied and addressed, and lessons should be learned. Studies indicated that the inability to diversify the economy away from energy-intensive industries was a key problem for energy conservation in the 11th FYP period (Lo and Wang, 2013; Song and Zheng, 2012). In fact, it is likely that the industrial energy efficiency programs in the 11th FYP period further stimulated the growth of heavy industries (Lo and Wang, 2013). Between 2005 and 2010, China increased its thermal-power generation by 63%, pig-iron and cement production by 74% and 76%, respectively, and vehicle production by 220% (NBS, 2006 and 2011). However, no new policies have been introduced to address the inability to diversify the economy considering the fact that, in 2011, the first year of the 12th FYP period, the economy grew by 9.2%, the industry sector by 10.7% and the heavy industry sector by 14.3% (NBS, 2012). Therefore, the role of economic restructuring

[6] Emission Reduction Target for 11th Five-Year Plan Accomplished ahead of Schedule. http://www.sgcc.com.cn/ywlm/mediacenter/industrynews/12/237549.shtml

and technological change in achieving energy conservation and emissions reduction needs to be strengthened.

Single pollutant control and single pollutant control technology would increase the cost and lower the efficiency. Preliminary data for 2011 indicate that nationwide SO_2 emissions continued to decline, but NO_x emissions increased by 7.2% (Xinhuanet, 2011). As a result of decreasing SO_2 emissions, the number of ammonium particles may actually increase since two ammonia molecules may form two NH_4NO_3 molecules instead of one $(NH_4)_2SO_4$ molecule. In other words, the benefits from SO_2 and NO_x emissions control in stabilizing or reducing SIA may be more than offset by a larger increase in ammonium nitrate than the reduction in ammonium sulfate. The policy implication is that an effective strategy to control secondary $PM_{2.5}$ (due to SIA) pollution over China needs to consider the interlinkages between air pollutant species and probably put more emphasis on controlling NH_3 emissions in the future (Wang et al., 2013).

Zhao et al (2012) and Song and Zheng (2012) found that the growth in economy, energy consumption, and atmospheric pollutant emissions have been larger in relatively less developed areas under current emission control and economic development polices. National air pollution control strategies will increasingly need also to address conditions in these areas in the future.

Zhao et al (2012) also warned that China's provincial and national energy statistics are often inconsistent. The Ministry of Environmental Protection (MEP) rejected 30-50% of SO_2 reductions claimed by some provinces during 11th FYP (Schreifels et al., 2012). Data verification should be further strengthened with the strengthening of binding targets.

Moreover, reliance on construction of pollution abatement equipment (end-of-the-pipe solutions) is a very limited approach to emission reduction. Cleaner production should be further promoted. Project quality, investment performance and operational efficiency need urgently to be improved.

The by-products of pollution abatement, e.g. gypsum from desulfurization equipment, should be treated in a systematic way. Market-based policies necessary for innovation are still in its infancy. Long-term mechanisms still need to be established. Health damaging pollutants such as $PM_{2.5}$ have yet to be controlled.

There has recently been some criticism of the most recent development in China's environmental policy, to some extent prompted by the severe pollution situation on Beijing and other areas during the winter of 2012-2013 (Parry, 2013). So far this seems to have been discussed mostly on blogs such as China Dialogue (Liu, 2013) and in mass media. A critical article in The Telegraph[7] builds in part on a report by Wu et al. (2013) who described an attempt to analyse incentives and outcomes of China's environmental policies. Their main conclusion was that city-level GDP growth is significantly positively related to greater odds of the city's top cadres [Party and government officials] being promoted. City-level environmental investment is, on the other hand, significantly negatively related to better odds of the city's top cadres being promoted.

5. Conclusions

The work carried out in this thesis shows that the economic costs of air pollution in Taiyuan 2000 were large, and that control strategies especially targeting area sources (low level distributed sources) could lead to substantial health benefits for the population in Taiyuan and that the gain is greater the earlier control actions are taken. Although there are large uncertainties in the estimates of health benefits and the implementation of air pollution control measures, the study has shown that scenario-based and pollution source-oriented health benefit evaluation of air pollution in Taiyuan can be very useful. Even though selection of optimal control scenarios

[7] Green politicians less likely to be promoted in China. http://www.telegraph.co.uk/news/worldnews/asia/china/9895100/Green-politicians-less-likely-to-be-promoted-in-China.html.

for Taiyuan requires further cost-benefit analysis and regional considerations, this study does provide decision-makers with evidence about not only the significance of control and prevention of environmental pollution, but also gives indications of what measures are most effective locally. The national air quality standard Grade II is quite high compared to the WHO guidelines (WHO, 2005), and the study implies that there are large health benefits to be gained by setting stricter standards for the future in China. China has already in 2012 set a new ambient air quality standard which lowers the previous threshold value of PM_{10} (Grade II: annual average from 100 $\mu g/m^3$ to 70 $\mu g/m^3$) and includes an index for $PM_{2.5}$ (Grade II: annual average 35 $\mu g/m^3$) for the first time.

The achievements in energy saving and emission reduction in Shanxi have been substantial in the 11th five-year plan period. The provincial and local governments have put energy efficiency and environment protection very high on its policy agenda, and devoted a considerable amount of effort to achieving the goals. Very detailed requirements and regulations have been issued. The most important measures so far seem to be in the industrial sector. However, Shanxi has still a long way to go to achieve satisfactory energy use and limit the emissions of pollutants such as SO_2, NO_x, CO_2 and PM. Further improvement of energy intensity and environment will require continuing efforts to optimize the economic structure in particular a shift to low-carbon economy and reduction in the dependence on heavy industry. The personnel appraisal system should also be improved to provide stronger incentives for achieving further energy intensity and pollution reductions.

6. Suggested future research activities

Future air pollution health research, especially long-term cohort studies, in China will need to examine the relevance of cumulative exposure, as well as to identify the most susceptible time periods and population groups, genetic-environment interaction, and pathophysiologic links between air pollution and cardiopulmonary diseases in Chinese population. As pollution reductions are likely to take place in many very polluted areas in China, this gives opportunities for ‘natural experiments’, i.e. studies of health effects of real world exposure reductions.

Considering that regional pollution is embedding most of China, local efforts to cut emissions are often insufficient. Thus, studies on both trans-provincial and megacity’s-boundary pollution effects and control strategies are urgently needed.

The synergies between energy targets and environmental targets need to be clearly articulated and analyzed.

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Papers

Paper I

The assessment of health damage caused by air pollution and its implication for policy making in Taiyuan, Shanxi, China.

Daisheng Zhang, Kristin Aunan, Hans Martin Seip, Steinar Larssen, Jianhui Liu and Dingsheng Zhang

Energy Policy (2010) 38: 491–502

Paper II

The energy intensity target in China's 11th Five-Year Plan period—Local implementation and achievements in Shanxi Province.

Daisheng Zhang, Kristin Aunan, Hans Martin Seip and Haakon Vennemo

Energy Policy (2011) 39: 4115–4124.

Paper III

Air Pollution reduction during China's 11th Five-Year Plan period - Local implementation and achievements in Shanxi province.

Daisheng Zhang, Kristin Aunan, Hans Martin Seip, Thorjørn Larssen, Haakon Vennemo, Steinar Larssen, Liulei Feng, Caixia Wu and Ruikai Xie

Environmental Development (2012) 4: 36–53.