Available online at www.sciencedirect.com
SCIENCE DIRECT
Journal of Cleaner Production 13 (2005) 57–70
Journal of Cleaner Production
www.elsevier.com/locate/jclepro

Cleaner production as climate investment—integrated assessment in Taiyuan City, China

Heidi E. Staff Mestl [a], Kristin Aunan [b], Jinghua Fang [c], Hans Martin Seip [b,d], John Magne Skjelvik [e], Haakon Vennemo [e,*]

[a] Oslo University College, Oslo, Norway
[b] CICERO Center for International Climate and Environmental Research, Oslo, Norway
[c] Department of Thermal Engineering, Taiyuan University of Technology, Taiyuan, China
[d] Department of Chemistry, University of Oslo, Oslo, Norway
[e] ECON Centre for Economic Analysis, Oslo, Norway

Received 6 March 2003; accepted 21 August 2003

Abstract

Taiyuan, one of the most polluted cities in the world, is the first cleaner production demonstration city in China. We assess energy related cleaner production projects in Taiyuan from the point of view of climate change and integrated assessment. In the assessment we develop a rather detailed methodology that relies on a battery of chained models All of the projects improve energy efficiency and reduce emissions. Still, we find that their environmental health benefit differs substantially. The projects are treated similarly from point of view of funding and the regularatory process. Yet, we find that their cost differs substantially, and there is no proportionality between costs and benefits. The finding could supplement explanations of cleaner production progress that rely on financial and institutional barriers. We also ask if the positive attitude to cleaner production in China may help the country introduce greenhouse gas saving projects under another name. It turns out that some, but not all of the projects we analyse have significant greenhouse gas reduction potential. The possibility for foreign funding as CDM projects is discussed.

Keywords: Environment; China; Co-benefit; Integrated assessment; Climate; CDM

1. Introduction

It is well known that greenhouse gas reducing investments can yield additional environmental benefits, sometimes called co-benefits ([1]; [4], [11]; [15]; [22]; [24]; [42]). These benefits may be especially large in developing countries. However, the methodology for estimating co-benefits of greenhouse gas reducing investments, called integrated assessment, is crude at some points. Using refined methodology this paper adds new evidence to the literature on integrated assessment of greenhouse gas reducing investments in the developing world.

Specifically, our objective in this paper is to estimate co-benefits of specific cleaner production projects in Taiyuan, the capital of Shanxi Province, China. Cleaner production projects improve production efficiency and eliminate waste within the process rather than at the end of pipe. Such projects are well suited for studying the co-benefits of greenhouse gas reductions since they tend to emphasize energy efficiency, technological upgrading and other measures that cut across a range of pollutants including CO_2, particle emissions and SO_2. But cleaner production projects are also interesting in a political perspective. They tend to receive rather more positive attention in the developing world than projects that go by the name of climate change. For instance, an international declaration on cleaner production has more than 1700 signatories, of which most are from the developing world. Twenty-four developing and transition countries, including China, India and other traditional climate skeptics, have at the moment established National Cleaner Production Centers to promote the practice of cleaner production [37]. If one can show that some cleaner

* Corresponding author. Tel.: +47-91-13-16-16; fax: +47-42-00-40.
E-mail address: haakon.vennemo@econ.no (H. Vennemo).

0959-6526/$ - see front matter
doi:10.1016/j.jclepro.2003.08.005

production projects are climate change projects by another name that even bring substantial co-benefits, it may remove some of the reluctance to climate change abatement that is found in developing countries.

Also, since cleaner production projects often reduce emissions of greenhouse gases they could be eligible for international funding through the Clean Development Mechanisms (CDM) of the Kyoto protocol. In order to qualify for such funding the projects must contribute to sustainability. The NGO community, especially, is eager to follow up on this point (see e.g., [18]). For these reasons as well, emphasizing co-benefits is essential.

The co-benefits that we estimate are compared to our estimate of ordinary costs. It is sometimes claimed that cleaner production projects are low-cost or no-cost options with a large benefit potential. It is the hope generated from such claims that is driving the establishment of Cleaner Production Centers in many countries. Yet, at least in China, implementation of cleaner production projects has been somewhat slow. This could indicate that project costs are higher than imagined, or it could indicate credit barriers or other barriers of an institutional nature. In any case it makes the costs of cleaner production projects an interesting object of study in its own right.

To discuss the co-benefits of cleaner production projects in relation to costs and CO_2-potential we rely on the impact pathway approach to environmental benefit estimation. This bottom-up approach estimates the monetary equivalent of environmental benefits. Starting from emission reductions associated with projects, and using a chain of models, one is moving forward towards end-points of physical health damage with associated monetary values. Adding over the end-points gives total monetary co-benefit. Subtracting the monetary value of environmental benefits from costs gives the net costs of CO_2 reductions related to cleaner production projects.

The impact pathway approach is becoming increasingly popular in studies of environmental improvements in China and elsewhere. Early forerunners include the ExternE project ([13], [14]) and the U.S. EPA project on the benefits and costs of the clean air act ([38], [39]). However, in China the physical and economic conditions are different from those in the US or Europe. An early application in China is Aunan et al. [4] who used the impact pathway approach to study clean coal technologies in Shanxi Province. Compared with Aunan et al. we consider specific projects planned or under implementation in Taiyuan and refine the model of air pollution dispersion. One advantage of this refinement is to analyze the distinction between low-stack and high-stack emissions, which turns out to matter a great deal for the co-benefit outcome.

The paper is structured as follows. Section 2 briefly reviews the environmental status of Taiyuan and the Cleaner Production programme there. Section 3 describes our approach and methodology. The methodology is applied to six representative cleaner production projects in section 4. Our conclusions are given in section 5.

2. Taiyuan: Environmental status and cleaner production plans

2.1. Environmental status of Taiyuan

Taiyuan City, the 3 million metropolitan area that is the capital of China's Shanxi Province, is generally recognized as one of the most polluted cities in the world. China's State of the Environment Report for 1999 [32] classifies it as the most polluted city in China. In 1998 the average annual concentration of SO_2 and TSP (total suspended particulates) was 278 μg/m^3 and 498 μg/m^3 respectively. These concentration levels are approximately five times higher than the thresholds for health risk set by the WHO and the EU. By year 2000 measured SO_2 concentrations had fallen to 200 μg/m^3 and measured TSP concentrations to 400 μg/m^3, but the situation is quite volatile and measurements are uncertain [16].

The reasons for Taiyuan's pollution problems may be found in the fact that more than 3/4 of industrial GDP is from polluting, heavy industries. The extent of state owned enterprises with old-fashioned technology and low productivity also matters. More than half of production is from state owned enterprises, and three quarters of urban workers of Taiyuan work in these enterprises ([27]; [33]). As a third factor industrialization in rural areas has increased coal consumption in town and village enterprises resulting in high emissions encircling the city.

It also adds to Taiyuan's pollution problems that the city is located in a basin surrounded by mountains on three sides and frequent inversions and low wind velocities enhance the concentrations of pollutants. The climate is dry and dust-mixed winds worsen the pollution problem [36].

2.2. Cleaner production in Taiyuan

In one of the efforts to improve the environmental situation, Taiyuan in 1999 became China's first cleaner production demonstration city. To implement its cleaner production program, Taiyuan intends to invest 1.5 billion Yuan (180 million USD) over the years to come. So far most of the projects are still at the planning stage, but some have recently secured funding. In addition to investment projects, the cleaner production campaign in Taiyuan, like in many other cities, has emphasized workshops for city officials and leaders, setting up cleaner production working groups in selected demonstration enterprises and developing local legislation for cleaner production. [12] and [19] provide overviews of cleaner production efforts in Taiyuan.

Cleaner production projects focus on several environmental burdens including hazardous chemicals in water emissions, industrial waste and energy utilization. It is the energy aspect of cleaner production that interests us here. Taiyuan has formulated a Clean Energy Action and Implementation Plan that covers the following categories of projects:

Clean coal technologies; covering low sulfur coal, coal sorting etc.
Clean fuel technologies; covering desulfurization, coke stove smoke treatment, motor vehicle emission reductions etc.
Central heating; covering central heating in residential areas and within factories etc.
Clean energy consumption; covering renewable energy projects.
Energy saving; covering waste heat recovery etc.
Supervision and control; covering monitoring devices etc.

The projects we choose for further analysis form a sample from these categories.

3. Our approach

3.1. General outline

Technically we follow the cost-benefit approach that is traditional in economics. In a bare-bone version a representative consumer obtains money-equivalent utility $V(m)$ from environmental air quality m. Air quality may be improved by abatement projects x, so $m = m(x)$. The cost of producing x is $c(x)$. The cost-benefit test says that a small abatement project dx generates net benefits if

$$V'm'dx - c'dx > 0$$

The term $V'm'dx$ is the gross value of co-benefits associated with the abatement project (with dx the project, $m'(x)$ the improvement in air quality resulting from the project, and $V'(m)$ the marginal money equivalent utility (willingness to pay) for this improvement). The term $c'dx$ is the economic cost of the project (with dx the project and c' the marginal economic cost). If the economic cost of the project is negative, the project is profitable. A profitable project generates net benefits independently of the size of environmental co-benefits.

The abatement projects that we are analyzing also reduce CO_2-emissions (by means of improving energy efficiency), that is, $co_2 = co_2(x)$. An abatement project contributes a decrease in CO_2, $dco_2 = -co_2'dx$ (dco_2 is then positive for an abatement measure). We define

Marginal (economic) cost of CO_2 reductions = $c'dx/dco_2$
Marginal social cost of CO_2 reductions = $(c'dx - V'm'dx)/dco_2$

On a project-by-project basis these ratios are central outputs of this paper.

3.2. Estimation of co-benefits

When estimating co-benefits by means of the impact pathway approach, we limit ourselves to health benefit as the research on co-benefit points to health as the far most important environmental impact. Compared with [4], which relied on simple coefficients of proportionality, we refine the model of air pollution dispersion in this paper. We also employ the value of life years lost (VOLY) approach to mortality impacts that in our opinion gives more accurate results than the traditional value of statistical lives (VSL) approach.

3.2.1. Emission reductions

We first estimate the particle emission reductions and the SO_2 emission reductions from the abatement options. Both are important for health impacts, but only particle emissions are used in our later quantifications. We also estimate the stack height of emissions, which is important for the next steps, dispersion and exposure. The projects that we are studying typically reduce emissions in process and in combustion. We call them direct emission reductions. Direct emission reductions occur at heights from 12–120 m. The projects also reduce electricity demand, which in Taiyuan most likely is translated to reduced electricity generation. Lower emission levels follow at the power plants, which we call indirect emission reductions. The indirect emission reductions at power plants occur at high stack height 180–230 m. We assume an emission factor of 5.0 kg/tons of coal equivalents (tce) for TSP, and 25.3 kg/tce for SO_2 for these emissions. These values are the same as applied by Aunan et al. [4] although the values there are given per ton raw coal. For industrial combustion we assume an emission factor for TSP (SO_2) of 11.1 (25) kg/tce unless otherwise stated.

Finally we estimate the CO_2-reductions associated with each project. The CO_2-reductions are caused by the energy savings of the projects. Similarly to direct and indirect emission reductions the energy savings take two forms, either as direct coal savings or as reductions in electricity supply from Taiyuan's coal-fired thermal power plants. To estimate the CO_2-reduction associated with each ton of coal savings previous authors use emission factors between 2.40 and 2.77 tCO_2/tce coal ([23]; [17]). We assume 2.40, which is in the low end, reflecting the low efficiency and incomplete combustion of coal in Taiyuan.

3.2.2. Dispersion modeling

To estimate the dispersion impacts of emission reductions we use the dispersion model AERMOD. AERMOD is a model developed by the U.S. EPA in collaboration with the American Meteorological Society (AMS) [40]. The model estimates the emission dispersion from multiple sources for varying terrain and meteorological conditions. The sources are point sources, area sources and volume sources. Concentrations are calculated at ground level or any chosen elevated position. It is also possible to obtain values at different elevations of a single grid point.

The model uses hourly measurements of temperature, wind direction, wind speed, and cloud cover. We have downloaded these measurements from [43]. Taiyuan has very frequent inversions, i.e. at a certain height in the troposphere the temperature starts to increase with height. In winter the inversion is at 500 m 80% of the time, whereas in summer it lies at 250 m 60% of the time. The air quality generally becomes poor during inversions. Temperature profiles with approximately correct inversion layers were given as input. Further the model needs values for albedo (fraction of the radiation reflected by the surface), surface roughness length (height above the ground at which horizontal wind velocity is typically zero), and Bowen ratio (the ratio of the sensible heat flux to the heat flux used in evaporation). These parameters are used to estimate the height of the so-called boundary layer, which is the layer close to the ground with highly turbulent mixing. Turbulent mixing facilitates dispersion of pollutants. The constants used, retrieved from [41], are given in Table 1.

The model gave good agreement with observations both for SO_2- and TSP concentrations. Further details are given in [25].

3.2.3. Exposure modeling

Applying the dispersion model, we calculated how the air pollution situation is likely to be affected by the emission reductions. To estimate changes in human exposure we have to know the population density throughout Taiyuan. This was estimated using population statistics in combination with a digital map of the city showing the residential areas [35]. We estimated the share of the population in each district that lives inside the area covered by our study. Moreover, comparing the population densities in sparsely populated counties relatively close to Taiyuan we found that these were 5–6% of the density in Taiyuan. Since the sparsely populated counties include some residential areas we judge that the difference in density between residential and non-residential (much of it agricultural) areas in Taiyuan is likely to be even larger than the ratio found from the county level comparison, and estimate the density in non-residential areas to be approximately 4% of the density in residential areas. The estimated population densities are shown in Table 2. The results from the dispersion modeling were then combined with the estimated population densities, giving estimates of how the exposed population throughout the city will be affected by the abatement options.

From the resulting exposure distribution, we calculated the weighted population exposure reduction for each option (ΔPWE). ΔPWE for an abatement option was calculated on an annual basis as:

$$\Delta \mathrm{PWE} = \frac{1}{P}\sum_i \Delta m_i \cdot p_i$$

where p_i is the population in area i, Δm_i is the reduction of the pollutant in area i, and P is the total population in the city. Use of the population weighted exposure reduction is warranted because the exposure-response functions are linear or close to linear in the relevant range of exposure reduction.

Table 1
Parameter values used in the dispersion model

	Winter	Summer
Albedo a_0	0.35	0.16
Roughness length r_0 (m)	0.5	0.5
Bowen ratio B_0	2.0	2.0

3.3. Exposure-response modeling

Exposure-response functions for a range of different health effects (‘end-points’) were used to estimate the health impact. The selection of exposure-response functions is based on a review of Chinese and international epidemiological studies [6]. We have calibrated the functions according to the present frequencies of different end-points in Taiyuan, or in Shanxi as a whole if data for Taiyuan were not available, as given in [34]. It is worth noting that for the end-points ‘number of hospital admissions’, ‘emergency room visits’ and ‘outpatient visits’, the frequency is considerably higher in Taiyuan than in Shanxi on average. The monetary valuation is based on [4].

To estimate the impact on mortality we applied the methodology described in [4], which enables us to estimate the number of avoided life years lost (i.e. life years gained) in the present and future population, for different age groups and at different points of time, due to changes in chronic exposure to small particle matter, PM_{10}. We applied results from [29] which indicate, as a conservative estimate, an increase in the mortality rate of 0.24% (95% confidence interval 0.001–0.770%) per $\mu g/m^3$ increase in PM_{10} concentration. This is considerably lower than the value proposed in the ExternE project [14], 0.39%) which was derived from [29] and used by

Table 2
Population, area and estimated population density in residential and non-residential areas within the study area

District	Pop. in study area	Residential area (km^2)	Non-residential area (km^2)	Pop. density—residential (pop/km^2)	Pop. density—non-residential (pop/km^2)
Ying Ze	399494	23	28	16761	670
Xing Hua Ling	510330	32	61	14740	590
Wan Bai Lin	404148	35	47	10931	437
Xiao Dian	353622	20	52	16277	651
Jian Cao Ping	295426	28	105	9150	366
Jin Yuan	157876	13	41	10653	426

Aunan et al. [4]. The value was applied uniformly on 5-year age groups between the ages of 30 and 90 in the 1999 Taiyuan life table. In addition, we applied a function for the impact of PM_{10} exposure on infant mortality given in [2] for the youngest age group (0–1 year). This function is based on two studies in the US and in the Czech Republic ([45] and [7]).

In order to connect these estimates to emission data we need to specify the size distribution of particles, indicated by the PM_{10}-fraction of TSP. A generally accepted fraction is 0.55, see e.g., [4]. However, as He et al. (2002) [20] point out, particulate removal techniques currently in use in China are effective with respect to coarser particles but do not remove small particles very well. On this basis we assume 0.7 in projects with efficient particle collectors, i.e. power production and process emissions (project 1–4 below), and 0.55 elsewhere (project 5–6). These assumptions fit baseline concentrations quite well.

3.4. Estimating economic costs

To analyze economic costs of projects we rely on engineering data describing the changes in inputs and outputs related to the projects. All projects save coal input or produce electricity output. One of them saves water. The cost savings from electricity and water are counted against the annualized investment costs of the projects (that is, the user cost of capital) to estimate the annual cost of each project. Note that the benefits are also on an annual basis. If the cost is negative the project gives a profit. In contemporary China prices of most goods are determined on the market, and we use market prices to estimate the costs.

In the calculations we assume water is priced at 0.27 US$/$m^3$, coal is priced at 20.3 US$/tce and electricity is priced at 0.06 US$/kWh. These prices are current, average prices on these commodities in Taiyuan and are converted to US$ at a rate of 1 US$ = 8.3 RMB.

To calculate the annualized cost of capital we need to know the real interest rate and the lifetime or depreciation rate. The real interest rate is difficult to pin down in China. Earlier, 8% has often been used for public projects with a social value, and 12% for commercial projects, but recently the real interest rate has dropped and we have used 6% in our calculations. 20 years lifetime of all investments is assumed. Note that the impact of assuming a too high interest rate or a too short lifetime is to underestimate the profitability of projects.

4. Project-by-project analysis

4.1. Description of projects and background variables

We analyze six cleaner production projects in Taiyuan. They form a fairly representative sample from the Clean Energy Action and Implementation Plan of Taiyuan that lists cleaner production projects in the city. Three of our projects are listed in the central heating category of the plan, with the three others coming from the clean coal and clean fuel categories. (Clean fuel actually means clean thermal fuel other than clean coal).

The projects were also chosen with an eye to data abundance and data reliability. Many of the projects in the plan are described rather vaguely and do not lend themselves to our analysis. That includes all projects in the clean energy (covering renewable energy) and energy saving categories of the plan. Still all of the projects that we do consider either save or produce energy.

Reliable data were found for four energy efficiency projects at the Taiyuan Iron and Steel Company that recently have been negotiated with the Japanese International Cooperation Bank. In addition we have reliable data for a central heating upgrading project and a project to build a briquette factory.

4.1.1. Projects and background data at Taiyuan Iron and Steel

Taiyuan Iron and Steel is the largest employer in Taiyuan with about 65,000 employees. The company is located in the northern part of Taiyuan city, within the residential/commercial areas. The company has 54 stacks at different heights releasing gases from combustion. Of these there are three stacks between 100 and 120 m tall. We assume two stacks at 120 m and one at 100 m (exit temperature 120 °C). The exact location and height of the remaining 51 stacks is not known, but we simulate them by assuming 8 small stacks with release height 30 m and 7 stacks with release height 60 m (exit temperature 160 °C). Only the emissions from the three tall stacks at 100 m and 120 m are involved in the considered projects. We assume that indirect emission reductions (from reduced electricity production) occur outside the Taiyuan Iron and Steel area.

In addition to the emissions from combustion there is also substantial dust pollution from the production, called process emissions. These emissions are both from low stacks at 20 m and within factory halls at ground level. Background data for TSP emissions from combustion and process at Taiyuan Iron and Steel is provided by [16]. Further details on the dispersion modeling are given by [25].

We proceed to briefly describe the projects (cf. Table 4).

Project no. 1, Coke Dry Quenching (CDQ). Compressed nitrogen gas is used to quench coke from 1000–200 °C in a process of coke dry quenching (CDQ). 1.1 million tons of coke at batteries no 5 and 6 of the coking factory at Taiyuan Iron and Steel will be quenched this way. The heat from the nitrogen gas will then produce steam to run a 3000 kW electrical power generator through a waste heat recovery boiler. The project will produce electricity and save water. In addition to direct emission reductions the electricity will indirectly save coal and emissions at the company power plant, see Table 4 for details. In total the project saves 153 tons of TSP and 340 tons of SO_2 annually (concise numbers reflecting point estimates, not accuracy). In the Cleaner Production Plan the project belongs to the clean coal category.

Project no 2, Electrical Arc Furnace (EAF). Six small energy-demanding and heavy-polluting electric stoves at the steel mill of Taiyuan Iron and Steel will be replaced with a big electrical arc-cast furnace. Each of the six existing stoves has a stack of 20 m. The stack emissions from the stoves have been measured to 7.9 kg/h TSP and the release temperature to 160 °C. In addition there are approximately 2400 tons TSP released annually within the factory hall. These emissions are modeled as a $100 m^2$ area source at 5m release height. We assume that 65% of the PM_{10} drifts out of the factory hall. A new efficient furnace will replace the six stoves and will emit approximately 195 t/a TSP. This replacement will eliminate the diffuse emissions and substitute the six existing stacks with one new taller stack. In addition electricity consumption is reduced almost 20%. In total the project saves 1440 tons of TSP, most of which is direct emissions (see Table 4), and 283 tons of SO_2. The Cleaner Production Plan has the project in the clean fuel category.

Project no. 3, Combined Cycle Power Production (CCPP). The project enables combined cycle power production using blast furnace gas. The project consists of a gas turbine, a heat recovery boiler and a steam turbine. It will use 200,000 m^3/h of gas to produce electricity from a 83,000 KW power generator. In addition the project will produce steam in the heating season. The emission reduction is 1112 tons of TSP, and 5540 tons of SO_2. The Cleaner Production Plan has the project in the central heating category.

Project no. 4, Top gas pressure Recovery Turbine (TRT). The project enables electricity production from excess pressure of blast furnace gas at the top of the furnace No.3. The capacity of the power generator is 6000 kW. Emissions of TSP are reduced 96 tons and SO_2 emissions are reduced 486 tons. All of this is indirect emission reduction; there is no direct reduction from this project. The cleaner production plan puts the project in the central heating category.

4.1.2. District heating project

Project no 5, District Boiler House (DBH). District heating is a growing source of heating in Taiyuan like in many other cities in China. The Heat Supply Plan of Taiyuan describes a plan to build of 30 big district boiler houses in the city to replace current small and inefficient coal boilers. The first four boiler houses are planned for completion by 2005, although funding is a problem.

Using data from the approved boiler house no. 1, we assume that three boilers will be installed in the boiler house with a total capacity of 157,000 kW. The new boilers and boiler house will replace 53 boilers and 16 boiler houses that currently serve a 2 km^2 residential area. The savings are estimated to 28,000 tons of coal annually (20,000 tons of coal equivalents). The new boiler house will emit approximately 220 t/a TSP from a 120 m stack. It will produce steam, mainly in the winter season to replace household coal consumption and coal consumption of small industries in the area. Household emissions of TSP modeled at 12 m release height will be reduced by 380 t/a, and emissions from small industries with release height 30 m will be reduced by 590 t/a. The net annual TSP reduction is thus 750t/a (970–220). The cleaner production plan puts the project in the central heating category.

4.1.3. Coal briquetting

Project no 6, Coal Briquetting (CB). The project consists of four coal briquette plants producing 1.0 million tons of coal briquettes with desulfurization additives, for industrial use. The purpose of this project is mainly environmental improvement. Building on [4] and references therein we estimate 30 percent emission reduction per unit of coal. In addition the project increases combustion efficiency by approximately 10% and saves coal. The total emission reduction is 3200 tons TSP/year, and 8640 tons SO_2/year. A release height of 30 m has been used for the dispersion modeling. The cleaner production plan has the project in the clean coal category.

4.2. Costs and emission reduction of projects

Table 4 presents the main data for the projects and their estimated costs. The projects have rather different costs and emission reduction potential. The combined cycle power production (CCPP) unit at Taiyuan Iron and Steel should be able to turn an annual profit of nearly 30 million USD while saving some 500,000 tons of CO_2. By contrast the electrical arc cast furnace at Taiyuan Iron and Steel (EAF) is scheduled to cost 6.7 million USD annually and save less than 30,000 tons of CO_2. These projects are the largest and the second largest investments in our sample.

The reason the CCPP unit is profitable lies in the large electricity production associated with the project. The production income overturns the large investment. The electrical arc furnace, however, is not able to generate huge amounts of electricity and does not save that much coal either. The result is a sizeable annual cost.

At this point we may note the difference between economic costs as calculated here, and financial costs. When estimating economic costs we value electricity production by the price of electricity for average purchasers in Taiyuan. This, we will argue, is the opportunity value of bringing additional electricity production to the market. It is by no means clear, however, that the CCPP project will be able to book the electricity production at the market price in its financial accounts. Since the electricity is an internal deliverance at the iron and steel company it is just as likely that the company will use a fairly low administrative calculation price to book the income. In that case the financial cost of the project will exceed the economic cost.

4.3. Environmental co-benefits

We proceed to discuss the co-benefits to health associated with the projects. Unit prices used for health effects are included in Table 3. Our estimates for weighted population exposure reduction, ΔPWE, and economic benefits due to reduced health damage of particles are given in Table 5. In all cases the benefit from life years gained contributes one third of the economic value. The largest health benefits are obtained with project 2, the electrical arc furnace at Taiyuan Iron and Steel Company Ltd. The large reduction in TSP emissions at a fairly low height is the reason for the large improvement. The other projects at Taiyuan Iron and Steel Company (projects 1, 3 and 4) have small local health benefits. The main reason is that the emission reductions, which almost all are associated with electricity production, are from high stacks. Outside of the Iron and Steel company project 5 (district boiler house) and project 6 (coal briquetting) generate large health benefits since the reductions in these cases originate at fairly low emission heights. Using the coal briquetting project as an example Fig. 1 graphically describes the impact of dispersion on air pollution concentration and population exposure.

Clearly, with our approach large co-benefits are only obtained if significant reductions in PM_{10} emissions occur at a fairly low height. For instance, emission reductions are not much larger at project no 2 (the electrical arc furnace), 1440 tons TSP, than at project no. 3 combined (cycle power production), 1112 tons. Yet the difference in economic health benefit is huge, 19 million USD versus 0.1 million USD. That high stacks relieve local health effects is a result in agreement with earlier work for instance by Wang and Smith (1999) [42]. However, it should be kept in mind that emissions from high stacks contribute to long-range pollution transport in China. Damage to crops and forests may be caused by particles [10], SO_2 and NO_x. SO_2 and NO_x are precursors of acid rain, which is a serious problem in parts of China [31]. However, in the Shanxi area the acidity is largely neutralized by natural and man-made alkaline dust. Still SO_2 may have direct effects on vegetation. NO_x is important for ozone formation, which may cause serious crop reductions [3]. Benefits of reducing the Taiyuan contribution to long-range transported pollutants are difficult to estimate but are likely to be substantial.

Several local environmental co-benefits have also been neglected. Reduction in concentrations of TSP, SO_2, and possibly ozone should improve crop yields in the area and reduce soiling and corrosion of materials. Due to a fairly dry climate, the material damage from pollution may be less than further south in China, but this needs further study.

4.4. Sensitivity analysis and uncertainties

The uncertainty in our estimates of health benefits is large and we devote space to discussing its magnitude. We start by indicating numerical sensitivity in our model framework. From this sensitivity, and in consultation with the literature we estimate the standard deviation of each major end-point. We use the estimated standard deviation to indicate confidence intervals for each end-point, and show how the intervals may be combined to indicate a confidence interval for total benefits from a project. The lower limit of this interval is of particular interest.

First we discuss vulnerability to meteorological conditions, using ΔPWE as an indicator of end-points. The rows marked Year 1 and 2 in Table 6 show results for the meteorological conditions for two years (from November 2000 and from November 2001, respectively). Results are given for all 5 projects resulting in significant health benefits. The difference is slightly above 10% for project 2 (arc cast furnace), and less for the other projects. The averages of the results for the two years were used in Table 5.

Table 3
Exposure-response functions for health effects

Health end-point (abbreviations)	Rel. coeff.[a]	Low[b]	High	Present freq.	Abs. coeff.[c]	Low	High	Unit price (US$)
Life years lost	See text							1992
Outpatient visits (cases) (OPV)	0.05	0.02	0.09	4.73	2554	1088	4068	12.5
Emergency room visits (cases) (ERV)	0.01	0.00	0.02	0.16	17	5	31	12.5
Hospital admissions (cases) (HA)	0.24	0.06	0.42	0.07	163	41	285	2500
Work day loss (WDL)	0.43	0.28	0.59	6.30	21955	14296	30635	1.75
Respiratory symptomdays in children (ARS-Ch) (person-days)	0.55	0.36	0.82	14.6	15096	9963	22694	12.5
Respiratory symptomdays in adults (ARS-Ad) (person-days)	0.27	0.20	0.33	14.6	32267	23665	39047	12.5
Chronic respiratory sympt. in children (cases) (CRS-Ch)	0.28	0.19	0.37	0.0035[d]	2	1	2	3700
Chronic respiratory sympt. in adults (cases) (CRS-Ad)	0.84	0.60	1.07	0.0035[d]	24	17	30	300
Asthma attacks (AA) (person-days)	0.06[e]	0.03	0.20	0.03[f]	1800	900	6000	1.00

[a] Relative coefficients and absolute coefficients indicate, respectively, the percentage change and the absolute change in annual number of cases per million people (all ages) per 1 μg/m^3 change in ambient concentration of PM_{10}.
[b] Low and high estimates represents tentatively ±1SD.
[c] The share of the population that is <14 yr of age (19%) is incorporated in the functions that apply to adults and children specifically. Thus, the functions are applicable to each unit of total population.
[d] Annual incidence rate from [26].
[e] Number of excess asthma attack per asthmatic.
[f] Frequency of asthma in the population (based on a study in Guangzhou, see [5]).

Table 4
Main data for projects including direct and total emission reductions

Project	Investment (mill USD)	Electricity generation or electricity savings (GWH/a)	Coal savings from electricity or directly (tce/a)	Annual cost (mill. USD/a)	Direct TSP (t/a); Height	Direct SO_2 (t/a)	Indirect TSP (t/a) Height 180–230	Indirect SO_2 (t/a)	Total CO_2 (t/a)
Project no 1 CDQ	24.1	18.1	7312	2.1	116; 100/120	155	37	185	17,549
Project no 2 EAF	61.5	27.7	11,194	6.66	1384; 5/20	0	56	283	26,866
Project no 3 CCPP	67.5	542	218,968	−27.6	17.5; 100/120	0	1095	5540	525,523
Project no 4 TRT	8.0	47.5	19,190	−2.1	0	0	96	486	46,056
Project no 5 DBH	15.7		20,000	1.8	750; 12/30	na	0	0	48,000
Project no 6 CB	17.5		100,000	0.4	3200; 30	8640	0	0	240,000

Based on feasibility studies, interviews with managers etc. in Taiyuan, winter 2002. Annual costs are estimated using the formula annual costs = annual investment costs − annual value of electricity production/savings − annual value of coal savings. See section 3.4 for economic data. Project 1 includes value of water savings, 0.097 million USD/a. Project 6 includes increased income from sales of briquettes. See section 4.1 for direct and indirect emission data. Total emissions consist of direct and indirect emissions.

Table 5
Estimated ΔPWE and economic benefit of abatement options (mill. USD)

	Project no 1 CDQ	Project no 2 EAF	Project no 3 CCPP	Project no 5 DHB	Project no 6 CB
Mortality	0.01	6.36	0.03	4.26	4.33
Outpatient visits	0.00	0.35	0.00	0.23	0.24
Emergency room visits	0.00	0.00	0.00	0.00	0.00
Hospital admissions	0.01	4.41	0.02	2.96	3.00
Work day loss	0.00	0.42	0.00	0.28	0.28
Acute resp. symptoms in children	0.00	2.04	0.01	1.37	1.39
Acute resp. symptoms in adults	0.01	4.37	0.02	2.93	2.98
Chron. Resp. symptoms in children	0.00	0.07	0.00	0.05	0.05
Chron. Resp. symptoms in adults	0.00	0.95	0.01	0.64	0.65
Asthma attacks	0.00	0.02	0.00	0.01	0.01
SUM	0.03	19.00	0.10	12.73	12.94
ΔPWE	0.01	5.24	0.03	3.51	3.57

Project no. 4 TRT left out since it generates no co-benefits at the two-digit level.

Fig. 1. Map of Taiyuan showing the effect of the abatement option "Coal briquetting". Contours show how the annual concentration of PM_{10} is reduced (μg/m^3). Graduated colour indicates the degree of population exposure reduction from the abatement option (calculated as ΔPM_{10} times population in each grid).

The meteorological model parameters in Table 1 were varied for project 5 (district boiler house). Reasonable variations in the albedo and Bowen ratio had little effects on the results. Changes in the roughness length of ±20% had also minor effects, but doubling the value gave an approximately 25% lower ΔPWE-value.

Results thus seem to be robust to changes in meteorological conditions. We move on to physical and technical conditions. For project 2 (arc cast furnace) the uncertainty is related to the emissions within the factory hall. We tried both to increase and decrease the PM_{10} emission rate with ±20%, denoted high and low in the table. The change in ΔPWE was proportional (±20%). We also tried to increase the emission height from 5—8 m. This had a minor effect on the results.

For project 6 (briquetting) the emission reductions take place at stacks modeled as area sources. In the base runs the emissions were assumed to occur between 20 and 40 m. We also made runs varying both average emission height and the height interval where emission occurs. The model run with height interval 25—35 m gave slightly less ΔPWE than the base run. Decreasing the height by 10 m increases ΔPWE by more than 50% while 10 m increase in the height results in a reduction of about 30%. The exact locations of the emission reductions implied by this project are not known. We therefore made a model calculation with less reductions in the most densely populated areas compared to the base run. This resulted in a nearly 25% reduction in ΔPWE.

Based on these experiments, which are summarized in the bottom five rows of Table 6, we find that results are sensitive to physical/technical conditions like stack height and emission rates.

Sensitivity of results to deviations in the dose-response functions can be derived on the basis of Table

Table 6
Values of ΔPWE for various assumptions. The meteorological conditions for year 1 were used in all calculations except in the row marked year 2

	Project 1	Project 2		Project 3	Project 5		Project 6	
Year 1	0.0068		4.95	0.0283		3.41		3.49
Year 2	0.0074		5.53	0.0280		3.62		3.65
		Low	3.83		Albedo 0.28	3.42	H 20 ±10m	5.51
		High	6.06		Albedo 0.42	3.40	H 30 ±5m	3.30
		H 8m	4.57		Bowen 1.6	3.41	H 40 ±10m	2.38
					Bowen 2.4	3.41	Other location	2.67
					Rough. 0.4	3.67		
					Rough. 0.6	3.20		
					Rough. 1.0	2.46		

3. However, the standard deviations given in Section 3.3 (see Table 3) do not represent total uncertainty in these functions. Since the functions are based on studies in other areas, the transfer to Taiyuan adds substantially to the uncertainty. We have applied functions from China when possible to minimize this uncertainty. However, there are so far no Chinese studies of chronic mortality, the most important impact, and we had to use results from the USA obtained for much lower particle concentrations than found in Taiyuan. According to [44], and discussed by Aunan and Pan [6], extrapolation of health impact slopes for PM_{10} beyond 150 μg/m^3 must be done with extreme care due to possible flattening of the curve. If the curve flattens we will overestimate the chronic mortality effect. On the other hand, the estimation of life years gained was found to give approximately half of the monetary benefit obtained by the more commonly applied method of estimating reduced mortality [4]. Further major contributions come from estimation of PM_{10} from TSP, and uncertainties in unit prices for effects.

The sensitivities of Table 3 and Table 6 have been put into context in a recent paper by Rabl and Spadaro (1999) [30]. They argue that, being products of independent variables, most distributions of individual end-points are close to lognormal by the central limit theorem. To obtain upper and lower bounds at the 68% confidence level the central estimate should be multiplied respectively divided by the standard error σ_g. To obtain the 95% limits σ_g^2 must be applied.

Rabl and Spadaro (1999) [30] move on to give subjective estimates of standard errors. They give $\sigma_{gi} = 2$ for dispersion. The results in Table 6 indicate that the value may be lower in our study. For instance, doubling the roughness length reduces our estimate 25%, which would correspond to $\sigma_{gi} = 1.33$. Although larger parameter changes would give larger deviations, we also take into consideration that the model base run gives reasonable concentrations for SO_2 and TSP compared to observations. For uncertainty in the exposure-response function, [30] gives $\sigma_{gi} = 2$ for transfer from other region and 1.3 for regression both for mortality and hospitalization. The latter value is lower than given in Section 3.3. The total standard deviation σ_g for chronic mortality is 4 according to [30]. For hospitalization the total standard deviation is 2.9.

Based on our own results in Table 3 and Table 6, which are lower than [30] in terms of dispersion, but higher in terms of exposure-response, we illustrate uncertainty in total health benefits by assuming σ_g to be 4 for chronic mortality and outpasient visits, 3.5 for work day loss and 4.5 for hospital admissions and respiratory symptoms (both acute and chronic). This means that the individual benefit estimates for chronic mortality and outpatient visits lie between [0.25μ, 4μ] for a 68% confidence interval, with μ being expected value. Individual benefit estimates lie between [0.06μ, 16μ] for a 95% confidence interval. Inserting for μ in the estimate for chronic mortality impact, project no 2 for instance, yields intervals of [1.59, 25.44] million USD and [0.38, 101.76] million USD respectively.

These are quite large uncertainties, especially for the 95% confidence intervals, but of course much of the uncertainty is irrelevant in the sense that it strengthens the tendency for co-benefits to overwhelm costs. We are interested in determining the lower benefit level that we can trust with confidence. We discuss such a lower benefit level, using project no. 2 as an example.

To calculate a lower benefit level we note that total expected benefits mainly are made up of the three end-points mortality, hospital admissions and acute respiratory symptoms (in children and adults). Taking lower limits of each of these end-points and adding, we obtain 4.00 million US$ for the 68% level and 0.93 million US$ for the 95% level. This means the probability that the true benefit is below 4.00 is at most 16%, and similarly for 0.93 (2.5%).[1]

However, the probability that each end-point simultaneously are below their lower level is less than 16%.

[1] 16% is obtained since the 68% level means there is 16% probability that the true value is below the lower limit, and 16% probability it is above the higher limit.

When end-points are stochastically independent, which seems a reasonable assumption in this case, sums and averages tend to revert to the mean, just as flipping two coins simultaneously tend to produce one head and one tail more often than two heads and two tails. To indicate the reversion to the mean we may again apply the central limit theorem. The central limit theorem applied to the three end-points yields 9.66 million US$ for the 68% level and 2.15 for the 95% level. Three addends are maybe too few for the Normal approximation to be close, however.

Two procedures have generated values of 4.00 and 9.66 for an indicated 68% level of total benefit in project no. 2, and similarly for the 95% level. We will argue that the true 68% level is between the values 4.00 and 9.66 million US$. As it happens, the cost of project no. 2, which we recall is 6.66 million US$, lies midway between the two values. We conclude that the probability that co-benefits of project no. 2 are at least 6.66, where the project gives net benefits independent of CO_2-reductions, is 84% or more.

4.5. Economic and social costs

Notwithstanding uncertainties a number of interesting observations are obtained from pulling together the estimated costs and environmental co-benefits as illustrated in Table 7.

The CO_2-reduction cost of the coke dry quenching (CDQ) project is more than 100 US$ per ton, and it has hardly any co-benefits. When introducing this paper we claimed that cleaner production projects may double as climate change projects that are eligible for CDM funding. The coke dry quenching project does not validate the claim. Without further funding support it is not competitive as a CDM project. The international CDM market currently quotes prices of around 5 US$ per ton with 10 US$ a possible price in the longer term (e.g., [28]). The CO_2-reductions would have had to be at least an order of magnitude larger for the coke dry quenching project to be competitive.

The next project on the list is the electrical arc furnace (EAF). In terms of economic costs of CO_2-reductions this project is in the high end. 250 dollars per ton CO_2-reductions is quite a lot higher than other alternatives. But then the project delivers co-benefits that in the central estimate bring net benefits of about 500 US$ per ton CO_2! The co-benefits of this project are uncertain, but our treatment of the uncertainty in section 4.4 indicates that they are at least as large as economic costs, and could be *much* larger. Factoring in the co-benefit turns an expensive project in terms of CO_2-reductions into a quite beneficial one per unit of CO_2. Part of the reason is that the CO_2-reduction is moderate. Given this situation the project is better described as one that primarily produces local and regional environmental benefit, with a CO_2-benefit on the side, than as a CO_2-project with local and regional co-benefits. The advantage of the integrated approach to environmental impact analysis is of course unaffected by such a switch of terms.

The combined cycle power production (CCPP) project is economically profitable. The economic profitability is close to 30 million US$. It also saves half a million tons of CO_2 and in contrast to the CDQ project obtains a negative social cost of CO_2 reduction of more than 50 dollars per ton. In contrast to the EAF project, the estimated co-benefits are negligible since emission reductions occur at high stack height.

The Top gas pressure Recovery Turbine (TRT) is economically profitable because of a huge amount of electricity generation compared to the initial investments. Since all the emission reductions of local pollutants are indirect and occur at high stacks, the estimated local benefits are insignificant. However, this project should be economically viable as a CDM project because of the negative costs per ton of CO_2 reduced.

The District Boiler House (DBH) project turns out to be expensive in terms of economic cost, but the cost is not outrageous. Besides, the project contains vast co-benefits and is obviously beneficial when these are factored in. The project could be defended as a CO_2-reduction project with highly significant co-benefits, or a project to reduce urban pollution with significant benefits for climate. China and other countries have in later

Table 7
Annual costs and benefits of CO_2 reductions

	Abatement Cost (mill. US$)	Local health benefits (mill. US$)	CO_2-reductions (tons)	Economic costs of CO_2 reductions US$/ton$CO_2$	Social costs of CO_2 reductions US$/ton$CO_2$
CDQ	2.1	0.03	17,549	120	118
EAF	6.66	19.00	26,866	248	−459
CCPP	−27.6	0.10	525,523	−53	−53
TRT	−2.1	0.00	46,056	−46	−46
DBH	1.78	12.73	48,000	37	−228
CB	0.4	12.94	240,000	2	−52
All projects	18.76	44.80	903,994	−20.75	−70.31

years invested heavily in district heating in order to reduce urban air pollution problems. The analysis of this project indicates that additional such investments are highly beneficial, at least in Taiyuan.

The briquette factory yields a cost in the 0–5 US$ range currently covered by CDM trading. The economic cost is low since the project saves as much as 240,000 tons of CO_2 at a cost of 400,000 US$. At 2 US$/ton CO_2 the estimated economic cost is substantially lower than the 27 US$ estimated by Aunan et al. [4]. That estimate was based on a nation-wide assessment of the price of briquettes (6 US$/ton coal) divided on the CO_2-reduction. Our estimate here is based on the investment cost of the factory, with a deduction for income from sales of briquettes. This estimate implicitly assumes that income from sales of briquettes has a counterpart in willingness to pay for briquettes, as opposed to a regulatory decree. This might be questionable. If 5.4 million US$ income from sales of briquettes is not deducted, estimated costs increase to 24 US$/ton CO_2. In any case the cost per ton CO_2 is overshadowed by the estimated co-benefits, which weigh in at about 54 US$/ton.

5. Conclusions

The paper has analysed the costs and co-benefits of six cleaner production projects in Taiyuan, China's first cleaner production demonstration city. Looking across the six projects we make the following observations. First of all, despite the fact that all projects increase energy-efficiency and save emissions, only three of the six projects obtain substantial co-benefits with our methodology. The primary reason for this is that emissions at stack height around 200 m have an insignificant impact on urban air quality and health compared with emissions at heights 30 m and down. This difference shows the value of detailed dispersion modeling when calculating co-benefits. Although the importance of emission height has been emphasized in earlier studies (see e.g. [42]), we know of no other study where the effects of emission conditions and meteorology on exposure have been studied in such detail for specific projects.

We consider the detailed modeling of the mechanisms leading up to exposure to be an important contribution of this paper to the methodology of co-benefit estimation and integrated assessment. The conclusion that stack height matters a great deal is confined to short-range impacts on urban air quality, however. Emissions of SO_2, NO_x and particulate matter may in addition contribute to long-range pollution transport, the formation of so-called secondary particles etc., which contribute to regional air quality. We leave the modeling of long-range pollution and secondary impacts for later research.

Our second main conclusion is that not all cleaner production projects are low cost options in terms of economic cost. For instance, four projects at Taiyuan Iron and Steel, which from the point of view of funding and the regulatory process are treated similarly, turn out to have significantly different economic costs. Two of the projects, the combined cycle power production and the top gas pressure recovery turbine, are definitely profitable in an economic sense, though they may be less so in a financial sense if they are not credited the full value of their power production. The two others are quite expensive options in terms of economic costs. Of these, the electrical arc furnace project generates very substantial co-benefits and it is clear that it should be pursued for non-CO_2 reasons. The coke dry quenching project does not have significant co-benefits to offer. In the literature discussing reasons for the (lack of) progress in implementing cleaner production projects, institutional and financial barriers have been prime explanations. Our analysis suggests that an additional explanation may be that some projects simply are expensive compared to benefits. Thus at least in Taiyuan the traditional explanation should be modified.

A third main conclusion from our research is that despite the high economic costs, all but one of the projects we have analyzed show negative social costs, that is, they generate net benefits. They generate net benefits to society that per ton of CO_2 go from 46 to about 460 US$. The total economic and environmental net benefit of the six projects amount to about 64 million US$ annually. That is a significant (and recurring) free lunch for a low-income city like Taiyuan and indicates that the cleaner production projects of the city may be well worth their costs. Moreover, most of the benefit would have been hidden by economic costs if not for the estimates of co-benefits. It is important to continue to collect evidence of co-benefits in developing countries and developed countries alike.

As a fourth conclusion, our research offers some support to the assertion made in the introduction that co-benefits are especially large in developing countries. We made that claim since emission reductions from a fossil fuel saving other things equal will be greater when there is little end-of-pipe abatement, as is typically the case in developing countries. On the other hand, willingness to pay for a given emission reduction will typically be lower in a developing country. With impacts of quantity and "price" going in opposite directions, the net effect on co-benefit is an empirical question.

Empirically we find co-benefits between 0–700 US$/ton CO_2. The average is 50 US$/ton CO_2. By comparison a recent paper by Burtraw et al. (2003) [9], for instance, estimates benefits of 3–4 US$/ton CO_2 in the U.S. Brendemoen and Vennemo (1994) [8] estimate 66 US$/ton CO_2 in Norway. Several additional estimates are surveyed by [21]. Most of them are below 50, which is why we find some support for the claim that co-benefits are greater in developing countries. However, the great variation in co-benefit estimates, both in this paper and in the literature, is perhaps more striking than disparities between developing and developed countries.

A fifth and final conclusion from our research is that cleaner production projects of the energy efficiency kind that we have studied do not necessarily double as climate saving projects of interest for the Clean Development Mechanism (CDM). We draw this conclusion from the fact that only one of the projects, the briquette factory, offers an economic cost below the current CDM benchmark of 5 US$/ton CO_2 and significant co-benefits that satisfy the requirement of sustainable development and lubricate the CDM transaction process. Another project, the combined cycle power production, offers a cost of –53 US$/ton CO_2, but in a sense this cost is too low. If the project is able to turn such a profit the additionality requirement of CDM may be questioned. The top gas pressure recovery turbine is in a similar situation with costs of –46 US$/ton CO_2. Still, it should be noted that the six projects in total save almost a million tons of CO_2.

The remaining three projects are more expensive in terms of economic costs than 5 US $/ton, but on the other hand two of them yield large benefits. From an integrated perspective they should be activated. There are surely many projects of this kind in the developing world. To break the funding deadlock for such projects a way to proceed could be co-financing between international CDM funds and domestic funding or foreign aid. This possibility deserves to be analyzed in more detail.

The large difference in co-benefits also suggests that a broad mechanism like the CDM fails in internalizing all benefits. The enforcement of environmental standards may therefore also be needed in order to limit emissions and avoid local emission hot spots.[2] More generally, when there are two policy objectives, local and global environmental improvement, clearly two (independent) policy instruments are needed to meet the objectives in an efficient way. More than two objectives require more than two instruments etc. Thus climate policy cannot do the job alone. One needs a hierarchy of environmental instruments in order to meet diverse environmental objectives.

The present study may be improved in several ways. Better estimates of reductions in concentrations of air pollutants may be obtained with more accurate data on emission reductions and meteorological conditions. The limited knowledge of PM_{10} in the emissions adds to the uncertainties. More accurate population densities would also be valuable. Clearly the dose-response functions need improvement especially when transferred from western countries. The unit prices for health effects are also largely based on western studies. Better health statistics from Taiyuan would improve estimates of health effects. Reductions in damage to materials and vegetation could be quantified at least roughly. More detailed project plans are necessary to improve the benefit-cost analysis and to evaluate projects as candidates for CDM.

[2] We thank a referee for this point.

Acknowledgements

Comments from Hu Tao and two referees are gratefully acknowledged. This work was financed by the Norwegian Research Council and the Norwegian Ministry of Foreign Affairs.

References

[1] Aaheim HA, Aunan K, Seip HM. Climate change and local pollution effects—An integrated approach. Mitigation and Adaptation Strategies for Global Change 1999;4:61–81.
[2] Aunan K, Fang J, Li G, Seip HM, Vennemo H. Co-benefits from CO2-emisison reduction measures in Shanxi—a first assessment. CICERO Working Paper 2000;2000:7.
[3] Aunan K, Berntsen TK, Seip HM. Surface ozone in China and its possible impact on agricultural crop yields. Ambio 2000;29:294–301.
[4] Aunan K, Fang J, Vennemo H, Oye K, Seip HM. Co-benefits of climate policy—lessons learned from a study in Shanxi, China. Energy Policy 2004;32(4):567–81.
[5] Aunan K, Li Z. Health damage assessment for Guangzhou—using exposure-response functions. Air Quality Management and Planning System for Guangzhou. NORAD Project 1996–1999. Technical Report B7. Kjeller: NILU—Norwegian Institute for Air Research, 1999.
[6] Aunan K, Pan X. Exposure-response functions for health effects of ambient air pollution for China—a review.
[7] Bobak M, Leon DA. Air pollution and infant mortality in the Czech republic, 1968–88. The Lancet 1992;340:1010–4.
[8] Brendemoen A, Vennemo H. A climate treaty and the Norwegian economy: A CGE assessment. Energy Journal 1994;15(1):77–93.
[9] Burtraw D, Krupnick A, Palmer K, Paul A, Toman M, Bloyd C. Ancillary benefits of reduced air pollution in the US from moderate greenhouse gas mitigation policies in the electricity sector. Journal of Environmental Economics and Management 2003;45:650–73.
[10] Chameides WL, Yu H, Liu SC et al. Case study of the effects of atmospheric aerosols and regional haze on agriculture: An opportunity to enhance crop yields in China through emission controls? Proceedings of the National Academy of Sciences 1999;96(24):13626–33.
[11] Cifuentes L, Borja-Aburto VH, Gouveia N, Thurston G, Lee Davis D. Climate change: Hidden health benefits of greenhouse gas mitigation. Science 2001;293:1257–9.
[12] CPWG. Promotion of Cleaner Production Demonstrative Provinces and Cities. Cleaner Production Working Group, China Council for International Cooperation on Environment and Development, 2000.
[13] EC. ExternE—Externalities of energy. Methodology, Vol. 2. Luxemburg: European Commission, Directorate-General XII, 1995.

[14] EC. ExternE—Externalities of energy. Methodology annexes. European Commission, DG XII: 1998. Available on: http://externe.jrc.es/append.pdf.
[15] Ekins P. How large a carbon tax is justified by the secondary benefits of CO2 abatement? Resource and Energy Economics 1996;18:161–87.
[16] EQRT. Environmental quality report for Taiyuan. Environmental Monitoring Center of Taiyuan, 2000.
[17] Fang J, Zeng T, Yang LIS, Oye K, Sarofim AF, Beér JM. Coal utilization in industrial boilers in China—a prospect for mitigating CO2 emissions. Applied Energy 1999;63:35–52.
[18] Hamilton K. Watchful eyes on emission projects. Environmental Finance 2002;June:32–3.
[19] He KB, Huo H, Zhang Q. Urban air pollution in China: Current status, characteristics, and progress. Annual Review of Energy and the Environment 2002;27:397–431.
[20] He H, Ortolano L, Shi H. Cleaner production in Taiyuan City, China. Innovative Environmental Technology Evaluation and Commercialization 2002b:2–34.
[21] IPCC. The evaluation of the ancillary public health impacts, chapter 8.2.4.1 in Climate Change 2001: Working Group III Mitigation. www.grida.no/climate/ipcc—tar/wg3/335.htm. Accessed July 10, 2003.
[22] Krewitt W, Heck T, Trukenmüller A, Friedrich R. Environmental damage cost from fossil electricity generation in Germany and Europe. Energy Policy 1999;27:173–83.
[23] Li S, Zhang K, Zhou F, editors. A collection of research papers on China's Energy and Environment. Press: China Environmental Science; 2000.
[24] LeeDavis D et al. Short-term improvements in public health from global-climate policies on fossil-fuel combustion: an interim report. The Lancet 1997;350:1341–9.
[25] Mestl HES, Fang J. Air quality estimates in Taiyuan. Application of a multiple source dispersion model. Cicero report 2003:01.
[26] Murray CJL, Lopez AD, editors. Global health statistics. A compendium of incidence, prevalence and mortality estimates for over 200 conditions. USA: Harvard University Press; 1996.
[27] National Bureau of Statistics. China statistical yearbook 2001. Beijing: China Statistics Press, 2001.
[28] PointCarbon. Carbon market Europe, March 21 2003, http://www.pointcarbon.com/wimages/Carbon—Market—Europe—21—March—2003.pdf, accessed July 10, 2003.
[29] Pope III CA, Thun MJ, Namboodiri MM, Dockery DW, Evans JS, Speizer FE, Heath Jr CW. Particulate air pollution as a predictor of mortality in a prospective study of U.S. adults. American Journal of Respiratory and Critical Care Medicine 1995;151:669–74.
[30] Rabl A, Spadaro JV. Damages and costs of air pollution: An analysis of uncertainties. Environmental Pollution 1999;25(1):29–46.
[31] Seip HM, Aagaard P, Angell V, Eilertsen O, Larssen T, Lydersen E, Mulder J, Muniz IP, Semb A, Tang D, Vogt RD, Xiao J, Xiong J, Zhao D, Kong G. Acidification in China: assessment based on studies at forested sites from Chongqing to Guangzhou. Ambio 1999;28:522–8.
[32] SEPA. Report on the state of environment in China 1999. 2000. http://www.zhb.gov.cn/english/SOE/soechina1999/air/air.htm.
[33] Shanxi Statistics Bureau. Shanxi Province Statistical Yearbook 2001. Bejing: China Statistics Press, 2001.
[34] State Statistical Publishing House. Health statistical yearbook of Shanxi—1996. Beijing: China Statistics Press, 1996.
[35] Statistical Bureau of Taiyuan. Taiyuan—50 years' Statistics, Statistical Bureau of Taiyuan. 2000.
[36] TCEAIP. Taiyuan Clean Energy Action and Implementation Plan, Science and Technology Commission of Taiyuan. 2000.
[37] UNEP. 2003. http://www.uneptie.org/pc/cp/ncpc/home.htm, accessed July 10, 2003.
[38] US-EPA. The benefits and costs of the clean air act, 1970–1990. Washington: Prepared for U.S. Congress by U.S. Environmental Protection Agency, 1999.
[39] US-EPA. The benefits and costs of the clean air act, 1990–2010. Washington: Prepared for U.S. Congress by U.S. Environmental Protection Agency, 1999.
[40] US-EPA. Revised draft user's guide for the AMS/EPA regulatory model—AERMO. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standard, 1998.
[41] US-EPA. Revised draft user's guide for the AERMOD meteorological preprocessor (AERMET). U.S. Environmental Protection Agency, Office of Air Quality Planning and Standard, 1998.
[42] Wang X, Smith KR. Secondary benefits of greenhouse gas control: Health impacts in China. Environmental Science and Technology 1999;33:3056–61.
[43] WeatherOnline. WeatherOnline UK & Ireland, Meteorological Services; 2002. http://www.weatheronline.co.uk/. Accessed June 2002.
[44] WHO (World Health Organization). Air quality guidelines. Geneva Switzerland: 1999. Available at: http:www.who.int/peh/air/Airqualitygd.htm.
[45] Woodruff TJ, Grillo J, Schoendorf KC. The relationship between selected causes of postneonatal infant mortality and particulate air pollution in the United States. Environmental Health Perspectives 1997;105(6):608–12.