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MONGOLIA

Air Quality Analysis of Ulaanbaatar
Improving Air Quality to Reduce Health Impacts

December 2011

THE WORLD BANK
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Sustainable development issues are an integral part of the development challenge in the East Asia and Pacific (EAP) Region. The World Bank's Sustainable Development Strategy for the region provides the conceptual framework for setting priorities, strengthening the policy and institutional frameworks for sustainable development, and addressing key environmental, social and rural development challenges through projects, programs, policy dialogue, non-lending services, and partnerships. The EASSD Discussion Paper series provides a forum for discussion on good practices and policy issues within the development community and with client countries.

The publication and primary data are available online at www.worldbank.eapenvironment and www.worldbank.org.mn

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Foreword

Air pollution has major health impacts on people living in Ulaanbaatar. The excessively high particulate matter concentrations, especially in the winter and in the ger areas, increase the incidence of heart and lung diseases, and lead to premature deaths. Improving air quality management in Ulaanbaatar and reducing pollution concentrations would prevent illnesses, save lives and avoid enormous health costs.

In order to get a sound information basis for a strategy to improve air quality in Ulaanbaatar, the World Bank in partnership with Mongolian counterparts launched an "Air Monitoring and Health Impact Baseline" (AMHIB) study in 2008. This was the first time that air pollution was monitored year round in the surrounding ger areas of Ulaanbaatar and that estimations of the health impacts from the monitored air quality levels were undertaken. The AMHIB study also includes analyses of the sources of the pollution concentrations, and cost-benefit analyses of measures to reduce these levels.

After the first AMHIB study phase, an initial assessment focusing on pollution concentrations and sources was published in December 2009. The preliminary results of the initial assessment indicated severely high particulate matter concentrations. After the year-round monitoring data, including measurements from the winter months, became available the full extent of particulate matter pollution was revealed, and even more alarming annual average concentrations and peak levels were found. This final report presents the results of the entire study including estimates of the massive health costs associated with air pollution and analyses of short-, medium- and long-term intervention options.

Despite the grave picture presented by this study regarding air pollution in Ulaanbaatar, it also allows for a positive outlook—the health burden due to air pollution in Ulaanbaatar can be significantly reduced through measures that have a favorable cost-benefit ratio. The AMHIB study has been carried out in close collaboration with our Mongolian partners, and we are looking forward to continuing this partnership with the aim of making a contribution towards a cleaner, greener and healthier Ulaanbaatar.

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Acronyms

AMHIB	Air Monitoring and Health Impact Baseline Study
ADB	Asian Development Bank
AirQUIS	Air quality Information System (developed by NILU)
AQ	Air quality
AQS	Air quality standards
ASTAE	Asia Sustainable and Alternative Energy Program
BC	Black carbon
CBDICFP (JICA)	Capacity building for development and implementation of carbon finance Project.
CHP	Combined heat and power station
CLEM	Central Laboratory for Environmental Monitoring
COI	Cost of illness
CP	Coarse particles (particles between 2.5 and 10 microns)
CVD	Cardiovascular diseases
EBRD	European Bank for Reconstruction and Development
EF	Emissions factors
EI	Emissions inventory
FRM	Reference method
GDP	Gross domestic product
GENT	Air monitoring equipment
GIS	Geographic Information System
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit (formerly GTZ)
GRIMM	Air monitoring equipment
GTZ	Deutsche Gesellschaft für Technische Zusammenarbeit
GW	Gigawatts
HOB	Heat-only boiler
ICD	International Classification of Diseases
IPCC	Intergovernmental Panel on Climate Change
IQR	Interquartile range
IT	Interim targets
JICA	Japan International Cooperation Agency
LPB	Low-pressure boiler
LPG	Liquefied Petroleum Gas
LV	Limit values
MCA	Millennium Challenge Account, USA
MJ	Megajoules
MMRE	Ministry of Mineral Resources and Energy
MNS	Mongolian standards
MNT	Mongolian currency (Tugrik)

MUB	MS owned by the Air Quality Department of Ulaanbaatar Municipality
MW	Megawatts
NAMHEM	National Agency of Meteorology, Hydrology and Environmental Monitoring of Mongolia
MS	Monitoring Station
NILU	Norwegian Institute of Air Research
NOX	Nitrogen oxide (combine nitric oxide/NO and nitrogen dioxide/NO_2)
NPV	Net present values
NRC	Nuclear Research Center
NRC- NUM	Nuclear Research Center (of the National University of Mongolia)
PM_{10}	Particulate matter (particles of diameter 10 micrometers or less)
$PM_{2.5}$	Particulate matter (particles of diameter 2.5 micrometers or less)
PMF	Positive matrix factorization
POP	Total population
PV	Present values
PWE	Population-weighted average exposure
RFF	Resources for the Future
RR	Relative risk
SA	Source apportionment
SCC	Semi-coked coal
SO_2	Sulfur dioxide
UB	Ulaanbaatar
UB CAP	UB Clean Area Project
UK	United Kingdom
UNEP	United Nations Environment Programme
US	United States
USEPA	United States Environmental Protection Agency
VSL	Value of statistical life
WB	The World Bank
WHO	World Health Organization
WTP	Willingness-to-pay

Note: Unless otherwise noted, all dollars are U.S. dollars.

Acknowledgments

The implementation of the *Air Monitoring and Health Impact Baseline* (AMHIB) study has brought together Mongolian and international air quality experts as well as public health experts and economists who have taken an synergetic approach of linking public health, air quality and economic issues. This report builds upon the discussion paper *Air Pollution in Ulaanbaatar: Initial Assessment of Current Situation and Effects of Abatement Measures* that was published in December 2009, and reflects the final results and recommendations from the AMHIB project.

In order to provide overall guidance to the project, a steering committee was set up and headed by Jargalsaikhan Ch, Vice Minister of the Ministry of Nature, Environment and Tourism (MNET). The committee included representatives from the Ministry of Health, Ulaanbaatar Government, the National Agency of Meteorology, Hydrology and Environmental Monitoring of Mongolia (NAMHEM), the Central Laboratory for Environmental Monitoring (CLEM) and the World Bank.

The Mongolian study team responsible for data collection, initial data analyses and initial drafting of technical background report, was implemented under a contract arrangement with the National University of Mongolia (NUM). The team was led by Sereeter Lodoysamba and included Dagva Shagjjamba and Gunchin Gerelmaa (Nuclear Research Centre, NUM), Altangerel Enkhjargal and Batbaatar Suvd (Mongolian Public Health Institute), Burmaajav Burmaa (Mongolian Ministry of Health),Lamzav Batnyam, Sarangerel Enkhmaa (NAMHEM) and Ganzorig Ayush (Department of Finance, NUM). In addition, a number of Mongolian researchers, students and officials have been engaged in the data collection processes performed as part of this study.

International team members engaged in drafting the main report and assisting the national team in the preparation of technical background reports on air quality monitoring, modeling work, health impact assessment and , abatement option scenarios and cost benefit analyses, included Steinar Larssen (World Bank consultan and chief technical advisor, former Norwegian Institute of Air Research/NILU), Bruce Denby and Liu Li (NILU), Bart Ostro (Office of Environmental Health Hazard, California EPA), Alan Krupnick (Resources for the Future/ RFF), Sandra Hoffmann (formerly RFF, now the Food Economics Division, US Department of Agriculture), Robert van der Plas (World Bank consultant) and Kristin Aunan (Center for International Climate and Environmental Research/CICERO). Technical assistance has also been provided by Qin Ping (Fudan University), Dam Vu Than (NILU) and Stephen Rauch (California EPA).

The project was co-managed by Ede Ijjasz (Sector Manager, China & Mongolia Sustainable Development Unit), Magda Lovei (Sector Manager, Social, Environment and Rural Development Unit), Arshad Sayed and Coralie Gevers (Country Managers for Mongolia), Jostein Nygard (task team leader) and Gailius Draugelis (co-task team leader). World Bank

team members included Stefan Csordas, Natsuko Toba, Neelesh Shrestha, Erdene Ochir Badarch, Tumentsogt Tsevegmid, Tijen Arin and Shawna Fei Lee. Administrative assistance was provided by Minhnguyet Le Khorami and Nomuuntugs Tsevegmid.

The report drafts have been peer reviewed by Dick van den Hout (Netherlands Organization for Applied Research/TNO), Jordi Sunyer Deu (Center for Research in Environmental Epidemiology), Mohammed Khaliquzzaman (World Bank consultant), Taizo Yamada (Japan International Cooperation Agency/JICA), Carlos Marcelo Bortman, Sameer Akbar, Hua Wang and Giovanna Ruta (World Bank). Additional comments were received from Dejan Ostojic, Robert W. Bacon, Jan Bojo and Paul Procee (World Bank).

The report has been edited by Robert Livernash and Charles Warwick, and designed and typeset by Shepherd Inc.

In addition to the outlined AMHIB donors, and by the request by the Mongolian Government, the World Bank has been cooperating closely with the Asian Development Bank (ADB), the European Bank for Reconstruction and Development (EBRD), Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), JICA, the Millennium Challenge Corporation (MAC), and many other partners in Mongolia to contribute to reduced air pollution in Ulaanbaatar.

We would like to express our gratitude to the various donors, who provided funds to carry out the study. This includes the Korean Environment Management Corporation (KEMC) (through the Bank-Korea Environmental Partnership), the government of the Netherlands (through the World Bank administered "Netherlands-Mongolia Trust Fund for Environmental Reform") and the government of Japan (through the Bank administered trust fund project "Capacity Building for the Development of Carbon Financing Projects in Mongolia"). The Norwegian Development Organization (NORAD) funded awareness raising through the *Together for a Green and Clean Ulaanbaatar Event* in June 2011, and dissemination seminars through its Eco-town program in Ulaanbaatar. Without this generous support, this study would not have been possible.

Executive Summary

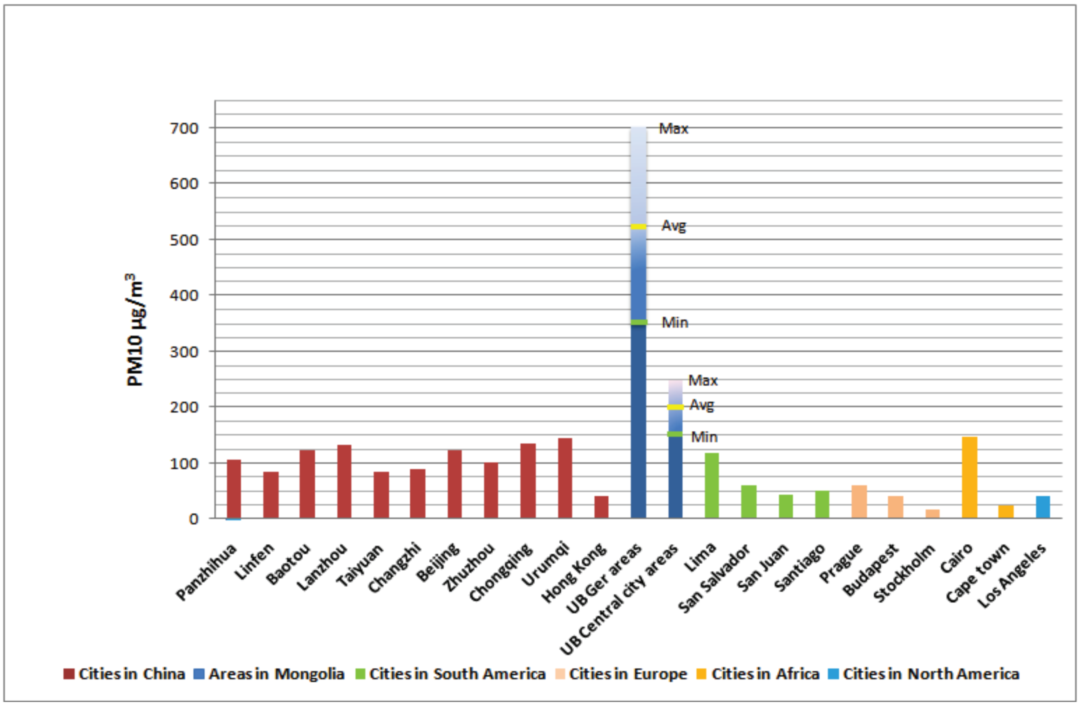
Ambient annual average particulate matter (PM) concentrations in Ulaanbaatar (UB) are 10–25 times greater than Mongolian air quality standards (AQS) and are among the highest recorded measurements in any world capital. PM is the main pollutant in Ulaanbaatar, and one that is of greatest concern due to its broader health impacts. This study thus focuses on monitoring and analyses of PM_{10} and $PM_{2.5}$ concentrations, particulates below 10 and 2.5 micrograms per cubic meter (μg/m³), respectively, which have known health impacts. Among all measurements taken at the study's eight monitoring stations, the worst recorded annual average concentration was more than 10 times higher than the Mongolian AQS for PM_{10} and 25 times higher than the Mongolian AQS for $PM_{2.5}$.[1] Compared to other cities for which data are available in global data bases, and also compared to Chinese cities with high PM concentrations, UB appears to be the most PM-polluted capital and is among the cities with the worst air quality in the world.

Ger households are both the main source and the main casualties of air pollution. Prior to this study, no systematic air quality monitoring had been undertaken in the ger areas of UB and continued data collection and analysis is recommended. The highest PM concentrations are measured in the ger areas, the location of the homes of the poor and the most vulnerable of UB's population. $PM_{2.5}$ concentrations in the ger areas are much higher than in the center, with an annual average concentration in the range of 200 to 350 μg/m³. The main sources of the particles in the ger areas are coal burning for heating and cooking during the winter, and the suspension of dust by wind action throughout the year, but especially in the warm season. Much of the ger areas were not included in the epidemiological study because area coverage of the monitors and the sample size was too small. Nonetheless, the health effects in the ger areas are likely to be substantially more severe than in the city center due to the high ambient PM concentrations. Assuming that the toxicity of $PM_{2.5}$ in the ger areas is generally similar to that in the city center and that the dose-response function (the calculation of the incidence of a health event due to inhaling excessive particulate matter of a given size) remains linear at the higher levels of $PM_{2.5}$, there is a 1.38 percent increase in daily mortality per every 10 μg/m³ in $PM_{2.5}$ in the ger areas. This suggests that the current $PM_{2.5}$ concentrations in the ger areas led to a 24 to 45 percent higher mortality than would be the case at the Mongolian air quality standard of 25 μg/m³. This constitutes a significant public health problem.

The main sources *of ground-level air pollution are coal and wood burning for heating of individual residences in ger areas and the suspension of dry dust from open soil surfaces and roads*, representing 75–95 percent of PM concentrations. Other significant sources of ground-level PM concentrations are emissions from power plants, heat-only boilers (HOBs), and car and vehicle exhaust.

[1] The Mongolian annual ambient air quality standards are 50 μg/m³ and 25 μg/m³ for PM_{10} and $PM_{2.5}$, respectively, while the WHO interim targets for developing countries are 70 μg/m³ for PM_{10} and 35 μg/m³ for $PM_{2.5}$.

Figure ES-1: Comparison of UB PM10 concentrations (2008–09) with Chinese cities (2008) and other world capitals (2004)



Source: Authors' illustration based on data from the China Environment Yearbook 2009 for Chinese cities, AMHIB study for UB, and WHO Air Quality Guidelines - Global Update 2005 for other cities.

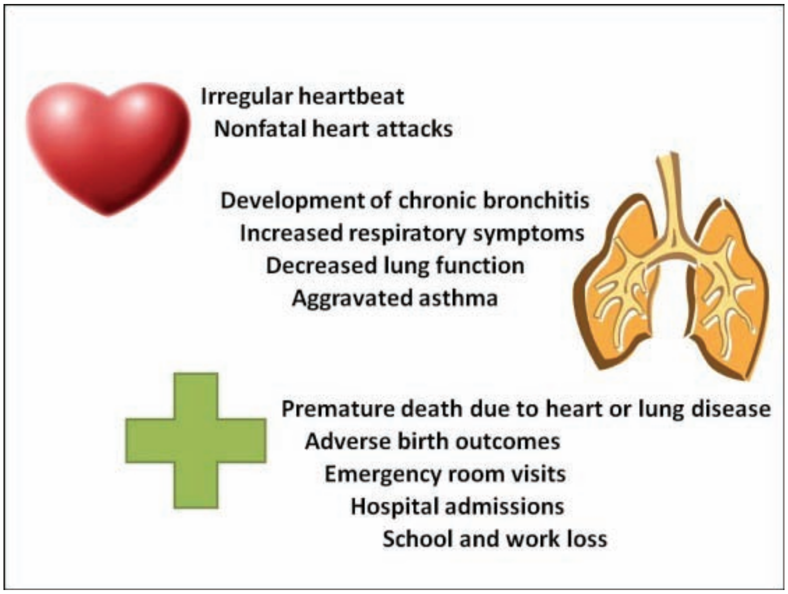
Table ES-1: Indicated ranges for annual average PM concentrations in Ulaanbaatar, June 08–May 09

Area	PM_{10} µg/m^3	$PM_{2.5}$ µg/m^3	Exceedance: Ratio to AQSs	
			Mongolian:	WHO
Central city areas	150–250	75–150	3–6	7–15
Ger areas	350–700	200–350	7–14	17–35

Source: AMHIB data

Wintertime PM measures show alarmingly high levels. PM concentrations during summer are much lower than during winter, therefore annual average figures mask alarmingly high monthly average and daily maximum PM concentrations during peak heating periods. Due to the dominance of ger stoves as emissions sources, PM concentrations in UB show a strong seasonal variation with the winter being much worse than the summer due to increased winter ger area heating. For example, monthly average PM_{10} concentration measured at the Zuun railway station in a ger area was 1,850 µg/m³ in January 2009, while the four highest daily average measurements at the same station were in the range of 3,612–4,360 µg/m³. The highest $PM_{2.5}$ concentrations were measured at the Bayanhoshuu station, also in a ger area, where the monthly average figure was about 1,500 µg/m³ and the five

Figure ES-2: Health Effects of particulate matter



Source: Authors' illustration.

highest daily concentrations were in the range of 2,310–4,060 μg/m³.[2]

There are also intra-day peaks when cooking takes place in the ger areas. Hourly measurements of PM correlate strongly with the daily routine firing practices of heating stoves, illustrating the importance of addressing emissions from cold-start lighting and refueling of stoves. Importantly, measurements generally corroborate the results from dispersion modelling, which is based on an emissions inventory and not the air monitoring station data, and on which abatement impacts are estimated.

The magnitude of the estimated negative health impacts is large. The alarming PM concentrations in UB lead to significant health impacts, amounting to estimated annual health costs of between $ 177 and $ 727 million (mean value $463 million). The health impacts were estimated, first, by setting a threshold value for population-weighted exposure, below which the health effect is very small. Second, modeling techniques were used to calculate exposure to excessive levels of ambient PM concentrations. The exposure of the population to pollution was estimated by calculating the physical dispersion of ambient concentrations of PM and then superimposing a population distribution. Third, the value of a statistical life (VSL), which is a function of the willingness to pay (WTP) for a reduction in mortality risk, was estimated based on a survey administered to a random sample of the population. The results show that the people of UB attach a high value to reducing mortality risk compared to cities in China as well as in the range typically measured in developed countries.

The epidemiological study shows statistically significant associations between cardiovascular mortality and coarse particles with a one-day lag*:* Every 10 μg/m³ change in coarse-particle concentrations would increase daily cardiovascular mortality on the next day by 0.25 percent. This means that a reduction of

[2] The concentrations measured on some days at individual monitoring stations are very high. However, no specific reasons have been found to reject these measurements. Although errors cannot be ruled out, they are regarded as examples of the very high exposures to PM that can occur due to a combination of very large emissions at low heights locally near the stations and adverse dispersion conditions.

coarse-particle concentrations by 200 µg/m³ would lead to a decrease in cardiovascular mortality by 5 percent. Likewise, for $PM_{2.5}$ each 10 µg/m³ increase relates to a subsequent 1.4 percent increase in daily all-cause mortality in the warm season so that a reduction of $PM_{2.5}$ concentrations by 200 µg/m³ would lead to a decrease in all-cause mortality of about 28 percent. In the cold season, a reduction of coarse particles concentration by 200 µg/m³ would lead to a reduction of mortality the next day by 5-6 percent. The strongest associations between particulate matter and hospitalization were between $PM_{2.5}$ and PM_{10} and cardiovascular disease. For each 10 µg/m³ change in $PM_{2.5}$, a 3-day lag was associated with a 0.82 percent increase in admissions for cardiovascular disease and a 0.24 percent increase for respiratory disease. For a 10 µg/m³ change in PM_{10}, a 3-day lag was associated with a 0.21 percent increase in cardiovascular admissions, while a 2-day lag was associated with a 0.04 percent increase in respiratory admissions.

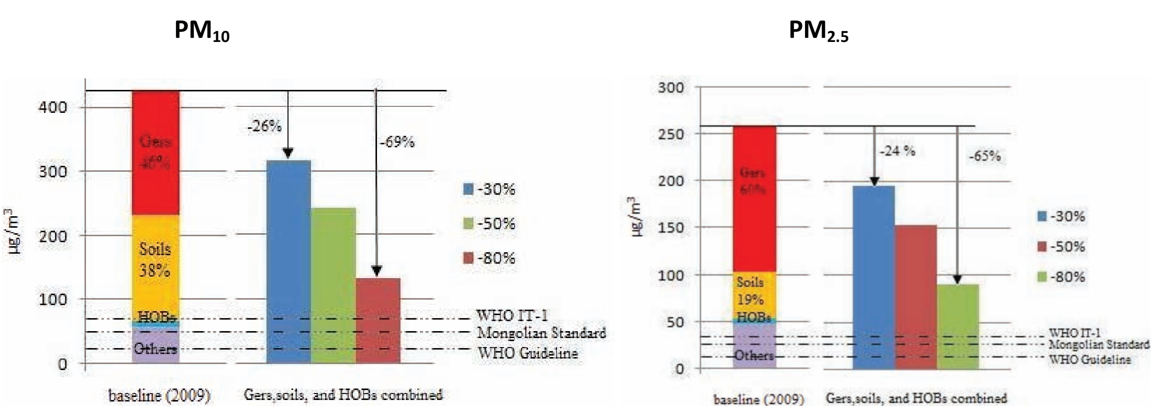
Abatement measures should demonstrate their emission reduction potential to ensure significant impacts on ambient PM concentrations. The study simulates reductions of ambient PM concentrations from reductions in emissions of key pollution sources. Simulations were made for of 30, 50, and 80 percent emissions reductions for the main sources. These results are shown in Figure ES-3. For example, an 80 percent emission reduction from coal combustion in ger areas, irrespective of the abatement measures used, yields an estimated 48 percent reduction in ambient $PM_{2.5}$ concentrations, or approximately $66 million in annual avoided health costs.

The results of this study show that a solution will require a wide range of pollution abatement options—there is no one magic bullet. An 80 percent emission reduction from ger area heating, heat-only boilers, and suspended soils (dust) yields a significant 69 percent reduction of ambient concentrations but is still not sufficient to meet Mongolian air quality standards. To achieve Mongolian AQS, an emission reduction of about 94 percent from these three source sectors would be needed.

Costs and benefits vary strongly between different pollution abatement options. Cost-benefit analysis helps to prioritize options that achieve emissions reduction targets. The study compared eight options, taking into account direct benefits (e.g. fuel savings), health benefits, and investment costs. The options are not

Figure ES-3: Air pollution concentration reductions due to emissions reduction of 30%/50%/80% (PWE of PM_{10} and $PM_{2.5}$ reduction)

Estimated population weighted average concentration for given emission reductions



Note: The projected emission reduction scenarios (-30%, -50%, and -80%) do not result in equal reductions in concentration values.

Source: Authors' illustration based on AMHIB data.

Table ES-2: Estimated current health damage due to PM and benefits and costs from air pollution abatement options in Ulaanbaatar

	Annual number of cases		Monetized (mill USD)			
	All-cause mortality (chronic)	Chronic bronchitis / Hospital admissions (Respiratory disease) / Hospital admissions (CVD)	All-cause mortality (chronic)	Chronic bronchitis / Hospital admissions (Respiratory disease) / Hospital admissions (CVD)	SUM (mill USD)	**Share of GDP in UB (2008)**
Current health damage	**1591 (385 - 2721)***	**1411 / 4465 / 4063 (1219 - 1516)* / (1828 - 8083)* / (2290 - 6122)***	**352 (85 - 601)***	**100 / 4.71 / 6.92 (86 - 107)* / (1.9 – 8.5)* / (3.9 – 10.4)***	**463 (177 – 727)***	**18.8 % (7.2 – 29.5)***
30% reduction of Ger stoves	63	74 / 619 / 528	14	5 / 0.65 / 0.90	21	**0.8 %**
80% reduction of Ger stoves	198	253 / 1663 / 1444	44	18 / 1.75 / 2.46	66	**2.7 %**
30% reduction of HOBs	3	3 / 28 / 24	1	0 / 0.03 / 0.04	1	**0.0 %**
80% reduction of HOBs	7	8 / 75 /64	2	1 / 0.08 / 0.11	2	**0.1 %**
30% reduction of suspended dust	53	60 / 520 / 443	12	4 / 0.55 / 0.75	17	**0.7 %**
80% reduction of suspended dust	159	199 / 1395 / 1205	35	14 / 1.47 / 2.05	53	**2.1 %**
30% reduction of all 3 sectors	129	159 / 1172 / 1009	29	11 / 1.24 / 1.72	43	**1.7 %**
80% reduction of all 3 sectors	**522**	**707 / 3169 /2822**	**115**	**50 / 3.34 / 4.81**	**174**	**7.0 %**

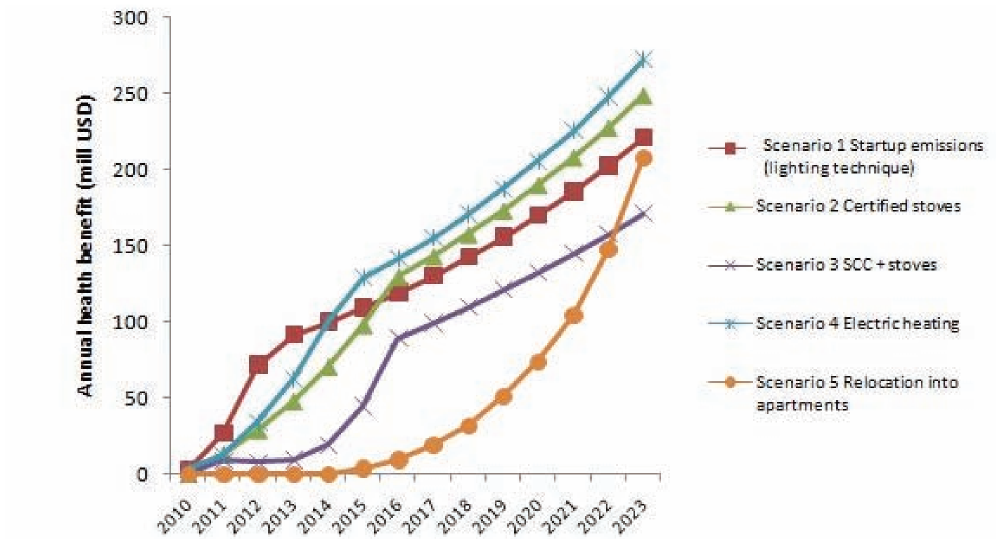
* These intervals were calculated based on the 95% confidence interval of the estimated dose-response coefficient and a +/– 30% interval of the PWE values. The lower (higher) value represents the estimate using the lower (higher) ends of both the 95% confidence interval of the dose response coefficient and PWE concentration. Similar confidence intervals apply to the estimated health damage reductions in the various scenarios but are not displayed here for the sake of clarity of presentation.
Source: AMHIB study

exhaustive of the abatement measures in UB, but represent some of the most discussed.

The costs of pollution management intervention include the costs of the program to promote the intervention (publicity campaign, training, possible subsidies, cost of testing and certification), cost of additional equipment needed (stoves, electric heaters, apartment buildings), cost of additional infrastructure needed (additional production capacity for clean fuels, electricity and/or heat, electricity/heat distribution network), and cost of incremental heating energy. Five of the scenarios generate a net benefit (avoided health costs minus abatement costs) in the range of $393–$1,635 million over a 15-year period. This suggests air pollution management can be carried out with a substantial economic gain when health costs are taken into account. The analysis requires continuous updating as new analysis on costs and emissions becomes available. For example, the Stove Emissions and Efficiency Laboratory in Mongolia has not yet been asked to test any fuel alternatives to Nailakh coal, the dominant traditional fuel, with cleaner stove technologies.

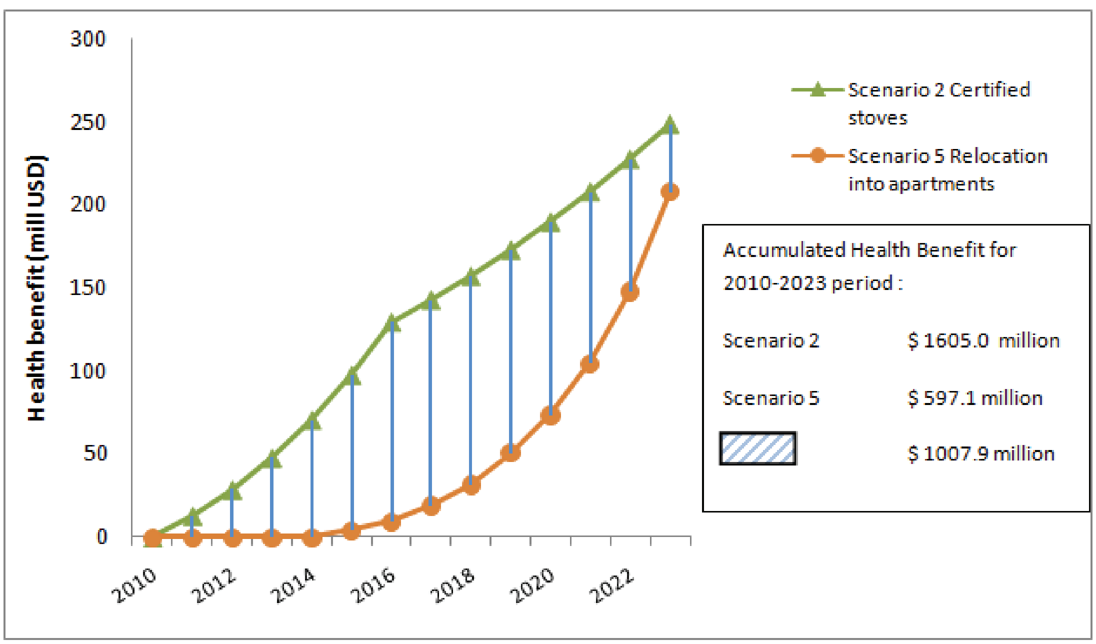
A strategy combining short- and medium-term pollution abatement measures is recommended. The sheer magnitude of the air pollution-induced health damage calls for immediate action, while medium- to long-term solutions are sought in parallel. Figure ES-5 illustrates the estimated cost of delaying short term actions, based on available information. The available options to manage air pollution and reduce health damage could take effect over the short (1–5 years) and long term (+5 years), depending on the nature of the intervention. Medium- and long-term solutions require preparation time during which people continue to breathe unhealthy air. Given the relative costs and benefits of various interventions analyzed in this report, fiscal and affordability constraints,

Figure ES-4: Annual health benefit from abatement scenarios (mill USD) (discounted values)



Source: Authors' illustration.

Figure ES-5: The cost of delaying short-term measures—the difference in health benefits between a short-term scenario (certified stoves) and a long-term scenario (relocation into apartments)



Note: Total estimated "*avoided cases*" by taking scenario 2 (certified stoves) compared to scenario 5 (relocation into apartments) in the 2010–23 period: 2,052 premature deaths, 2,666 cases of chronic bronchitis, 16,775 cases of respiratory diseases (HA), 14,615 cases of cardiovascular diseases (HA).
Source: Authors' illustration.

and the time needed for adequate preparation, the following strategy is recommended:

a. Set targets that would reach Mongolian AQS for PM_{10} as soon as possible and $PM_{2.5}$ by 2020; given socioeconomic constraints, set interim targets and a reduction time line for PM pollution reduction.
b. Ensure that abatement measures have reasonable, demonstrated emission exposure reduction potential that is sufficient to contribute significantly to achieving targets.
c. To achieve targets, all main PM sources need to be tackled, but these should be prioritized based on the potential of their emissions exposure reduction, costs, affordability, and the level of preparation and time required for implementation, ease of implementation, and governance issues. Reductions are needed first from ger heating systems (stoves, wall stoves, and low-pressure boilers) and from dust suspension from uncovered soil surfaces, as roads, and near-road surfaces are the second most important PM_{10} source.
d. Maintain an open and candid discussion of actual costs and benefits of abatement measures by (i) ensuring the abatement measures are technically feasible and their emission reduction benefits are justified with sufficient evidence; (ii) appraising the full costs of abatement measures and their contribution to overall improvements in ambient PM concentration reductions, so they can be compared to the health cost reductions; (iii) if subsidies are provided, avoid over subsidization to ensure sustainability; and (iv) keep the public informed of plans, manage expectations and find opportunities to mobilize citizen action.
e. Implement concerted actions that combine (i) short-term measures that are well-prepared and can be carried out in a relatively short period of time (1–3 years) to have a visible effect, (ii) medium-term measures that require more resources and time to prepare and roll out.
f. Introduce an interagency coordination mechanism with the UB city and central government with a *working level secretariat* that will be responsible for year-round monitoring, gathering and processing information on all abatement programs (government, donor and private initiatives), providing research and support to this coordination body, and supplying the government and UB city with up-to-date information on program progress, latest news, as well as private sector for information and coordination. The GoM and UB city have already implemented elements of this strategy, which is supported by the donor community, including the United States Millennium Challenge Corporation, Asian Development Bank, European Bank for Reconstruction and Development, Japan International Cooperation Agency, United Nations Environment Program, the World Bank, and bilateral programs from the Netherlands, Korea, Germany and France.
g. Strengthen air quality monitoring and have sufficient operating budgets in place to evaluate the results of various efforts to reduce ambient concentrations of PM and the effectiveness of key strategic programs, such as the replacement of ger stoves.
h. Strengthen air quality emissions inventories for dispersion modeling.
i. Maintain and strengthen the Stove Emissions and Efficiency Testing Laboratory, set up by ADB under the auspices of the Ministry of Mineral Resources and Energy, which can test emissions factors for new stove models and support clean stove technology development.
j. Continue studies of health impacts.
k. Maintain public awareness through a professional public awareness campaign that can adequately distill technical messages, and monitor results and other information to build knowledge and understanding. The secretariat of the coordination mechanism could be a focal point for this effort with the support of a professional public relations agency.

This study concludes that it is important to establish a well-coordinated framework for pollution abatement in Ulaanbaatar—one that relies on best available scientific and economic data, that involves its citizens and shares information with them, and continuously updates urban air quality analysis, such as the one presented in this study, based on new information as it becomes available. Concerted efforts, over several years, are needed. Table ES-3 shows air pollution, health effects, and abatement options in UB at a glance. The study's interim findings have been shared with UB citizens, MUB, GoM, and the donor community since its inception. The study was largely conducted by Mongolian institutions, especially the National University of Mongolia, the Ministry of Health's Public Health Institute, and the Mongolian National Agency for Meteorology, Hydrology, and Environment Monitoring, under the guidance of the AMHIB Steering Committee chaired by the Ministry of Nature, Environment and Tourism and including the participation of the Ulaanbaatar Municipality's Air Quality Agency. The previous National Coordination Committee on the Reduction of Air Pollution in Ulaanbaatar (NCC), chaired by the Minister of Mineral Resources and Energy and vice chaired by the UB Municipality, were informed of the interim results. This committee has now been replaced by a similar NCC headed by the president of Mongolia. Mongolian experts involved in this study have participated in the drafting of new programs, policies, and legislation. This process should continue. Ulaanbaatar is already the world's coldest capital city; it need not be the most polluted.

Table ES-3: Ulaanbaatar air pollution burden at a glance, 2008/09

		Source	PM_{10}	$PM_{2.5}$	Spatial distribution
Air Pollution	Emissions (tons/year)	Ger households	19,731	15,785	Throughout Ger areas
		HOBs	1,077	646	Dispersed over UB surroundings
		CHPs	18,589	7,436	3 point sources to the west of UB centre
		Vehicle exhaust	1,161	1,161	Mainly throughout the central city areas
		Dust from paved roads	9,954	771	Mainly throughout the central city areas
		Dust from unpaved roads	4,812	722	Mainly throughout the Ger areas
	Concentration (μg/m^3)	Central city areas	150–250	75–150	Ger areas show much higher concentration levels
		Ger areas	350–700	200–350	
Health Effects	Exposure (μg/m^3)	Population weighted average	427	260	Ger households are exposed to higher levels of air pollution
	Mortality and Hospitalization	Reduction in μg/m^3 and associated health benefits	200		~4.2% in cardiovascular admissions ~0.8% admissions for respiratory disease
			200 μg/m^3 reduction in coarse particles		~5–6% all-cause mortality in cold season ~5% in cardiovascular admissions
				200	~28% all-cause mortality in warm season ~16.4% admissions for cardiovascular disease ~4.8% admissions for respiratory disease ~27.6% in all-cause mortality in Ger areas
	Willingness to Pay	Value of statistical life: US$ 221,000			
	Health Costs	**Current health damage corresponds to 19% of GDP in Ulaanbaatar and 9.1% of GDP in Mongolia**			

				NPV costs (million US$)	US$ per t reduced	PV health benefit (million US$)	Net Benefit (million US$)
Cost Benefit Analysis	Emission Control Scenarios and Health Benefits	Reduce start-up emissions through backlighting the fire	-39%	-53	-463	865.8	918.8
		Reduce start-up emissions through slight modifications of the stove	-58%	-35.8	-208	1,599.0	1,634.8
		Replace existing stoves with cleaner coal stoves, without changing the fuel	-26%	-0.3	-4	1,605.0	1,605.3
		Replace existing stoves and fuels with cleaner stoves and SCC	-22%	36.7	550	1,028.5	991.8
		Electric heating in existing Ger homes	-63%	1,410.0	7,523	1,802.9	392.9
		Relocation of Ger households into apartments	-31%	4,094.0	44,925	597.1	-3,496.9
		Heat-only Boilers	-32%	5.9	49	19.7	13.8
		Road dust	-1.7%	66.7	39,332	66.9	0.2
		Greening	-0.2%	2.5	18,016	58.1	55.6

Source: AMHIB data.

1. Introduction

Previous studies of air pollution in Ulaanbaatar and the AMHIB air pollution study

Ulaanbaatar's population has likely been facing air pollution challenges for several decades—through the development of Ulaanbaatar (UB) as a growing industrial city with increased construction, traffic, and power generation facilities located in a valley with a relatively dry climate. But it was the rapid expansion of the surrounding ger[3] areas that started to indicate that UB was facing severe air pollution challenges. The Mongolian government had established an air monitoring system within the traditional city center, but it largely monitored SO_2, NO_2, temperature, and wind direction. Nevertheless, knowledge about air pollution—especially particulate matter (PM), the pollutant with the most destructive impact on human health—was limited. At the National University of Mongolia (NUM), sporadic PM_{10} and $PM_{2.5}$ monitoring began on a very limited scale in 2004–05 with incomplete yearly collected data sets. However, it represented a start, indicating the growing concern in the city's air quality situation.

The World Bank first started to examine the air quality situation in UB with the initial development of the UB Clean Air Program. Prior to the preparation of the program, the Bank decided to take a closer look at the PM levels in UB by estimating PM concentrations based on an initial source inventory made available to the Bank consultants. This contributed both to the estimates of PM concentrations and to a first understanding of the PM source structure (Guttikunda 2007).

Through further development of the UB-Clean Air Program, it was discovered that the Mongolian authorities already had established some PM monitoring on a research basis, estimating both actual PM concentrations levels as well as chemical composition, through which an initial understanding of the PM source structure emerged. This information was also circulated within the UB government and environmental authorities.

UB covers a relatively large geographical area. It has a population of about 1 million with diversified living conditions in the traditional city center and the emerging surrounding ger areas. To monitor these areas, the World Bank, in close cooperation with their Mongolian counterparts, established an Air Monitoring and Health Impact Baseline (AMHIB) study. The study was intended to create an air quality baseline from June 2008 to May 2009 which would then be used to compare changes in the city's air quality. Simultaneously, a health impact assessment was also undertaken in approximately the same locations as the AMHIB air quality monitoring network. The system included eight monitored locations distributed among traditional city and ger area locations.

In December 2009, the preliminary results from the AMHIB work were presented (World Bank 2009) reflecting results from the first few months

[3] Gers are round removable wooden homes traditionally used by Mongolian (and other Central Asian) nomads. Today, UB's city center is surrounded by gers with non-populated rural areas beyond the ger areas.

of operations. In addition, the emissions inventory used for the work was presented along with initial modeling results, based upon the initial knowledge of PM concentration levels and source structure.

This report presents the final results of the AMHIB study. The main audience for this study is the government of Mongolia (GoM) and Ulaanbaatar decision makers, as well as those actively engaged in the improvement of the city's air quality, including air quality professionals, health experts, and development partners. The study contains (a) the results of air quality monitoring from June 1, 2008, to May 31, 2009 in eight locations, including for the first time in the city's ger areas; (b) the outcome of air quality modeling to predict the effects of various pollution abatement measures; (c) a comparison of over 50,000 hospital records in six of nine administrative districts in UB to correlate the incidence of cardiovascular and respiratory disease, and premature death, caused by exposure to excessive particulate matter (PM) pollution; and (d) a willingness-to-pay survey of 629 respondents in Ulaanbaatar to estimate the value placed by UB residents on avoiding premature diseases and mortality, thus providing a basis to quantify the health costs of air pollution and the benefits of reducing air pollution. The report shares the findings of these efforts and recommends an air pollution reduction strategy. We hope this study marks the beginning of a continuous assessment of issues and options as new information and data is learned on solutions to this severe public health crisis.

Objectives of this report

By including the first components in an air quality management concept, the AMHIB study intends to establish a baseline for air quality and health impact measures upon which future air pollution control activities can be compared. By showing the PM concentration levels at the various AMHIB monitoring stations in the 2008–09 period, it is possible to compare the development over the future years in both ger areas and traditional city centers.

The objective of the report is also to estimate the effects of PM concentrations on human health, both mortality and morbidity, through chronic bronchitis and cardiovascular and respiratory system diseases. Finally, the objective is to present abatement scenarios to cost-effectively reduce the high PM concentrations.

Scope of the project

The aim of this study is to inform decision makers about the sources of air pollution in UB, the health damage caused by PM, and the options for abatement measures. The results and recommendations of this study neither represent a full and final treatment of air pollution in UB, nor do they provide a complete treatment of all available options for intervention or prescribe a specific course of action. Rather, this report intends to highlight the nature and scale of air pollution and associated health costs, and outline some possible interventions to address this issue. Certain aspects of air pollution management such as capacity constraints, institutional issues and social acceptability have not been included and the statistical analyses underlying this report are subject to a number of sources of uncertainties. The report has to be read with these caveats in mind, and should therefore be viewed as an information source for designing policies aimed at addressing air pollution in UB, rather than a detailed air pollution management strategy.

In many developing countries indoor air pollution is more severe than outdoor air pollution, particularly because of indoor heating and cooking practices and the use of charcoal, wood etc as fuel. However, in UB the design of ger stoves means that PM is absorbed through the stove chimneys, thereby resulting in relatively less severe indoor air pollution. Indications show that outdoor air pollution is substantially graver than indoor air pollution (see box below). As a result, the report is focused on outdoor pollution.

The report focuses on local air pollution impact on health caused by PM from main pollution sources. Therefore, the report identifies the main sources that contributes to PM concentrations in Ulaanbaatar, the health and economic effect of these high concentrations and how to reduce the emissions and contributions from these sources. In that context, it should

be noted that certain sources may in general contribute to high air pollution concentrations, for example combined heat and power (CHP) stations would be critical contributors to overall sulfur dioxide (SO_2), PM, carbon dioxide (CO_2) and greenhouse gas (GHG) emissions and concentrations. However, since the focus of this study is on PM emissions and concentrations in Ulaanbaatar, we have restricted the report mainly to a focus on the main sources of the high PM concentrations in which CHPs seem to be a more limited source (e.g. due to their high stacks).

This does not mean that CHPs are not important sources to focus on in an overall air pollution management plan; they certainly are and initiatives to reduce emissions from CHPs play an important role in controlling overall air pollution emissions (e.g. SO_2 contributions in a regional context and CO_2 in a global context).

Similarly, other analyses, such as on greenhouse gases (GHGs) quantification and Syngas potential have not been considered as they lie beyond the scope of this study.

Comparison of indoor air pollution with the outdoor air pollution concentrations

In 2008, a comprehensive Indoor Air Pollution (IAP) study, "Indoor Air Quality Survey" was undertaken in UB by the Ministry of Health (MoH), Public Health Institiue (PHI) and WHO. The annual average concentration values of PM_{10} and $PM_{2.5}$ from the study are much lower, particularly in gers, than the measured values in the AMHIB study for outdoor air pollution.

Indoor air pollution concentration vs outdoor air pollution concentration (PM_{10} and $PM_{2.5}$)

	PM 10 (ug/m3)	PM 2.5 (ug/m3)
Indoor Air Quality Survey (2008)*	117.91	55.16
AMHIB Outdoor air pollution study (2011)** (year round)	350-700	150-250

* Study conducted during March-June 2007
** Study conducted throughout the year of 2009

2. Air Quality Management Approach

Air Quality Management Concept

Given the complex nature of air pollution problems in Ulaanbaatar, integrated air quality management is recommended. Used in successful air pollution abatement programs world-wide, this is a structured approach to a *continuous cycle* of planning, implementing, evaluating, and adjusting abatement strategies and measures. This includes (a) an assessment of air quality and its distribution and variations in order to understand pollution levels, and the contributions from various sources to ground level concentrations; (b) an assessment of the environmental damage caused by air pollution and the effects of exposure to air pollution on the population; (c) identification and assessment of feasible abatement options; (d) a cost-benefit analysis to compare costs of abatement options with decreases in costs in pollution-related damages; (e) prioritization of abatement measures based on selection criteria that should include technical feasibility, ease of implementation (e.g. does the locality have the capacity to implement), and the rate of return of the abatement measure in terms of the value of reduced damage costs; (f) design of a pollution abatement strategy; (g) implementation; and (h) monitoring and evaluation to provide feedback for continuous readjustment and improvement.[4]

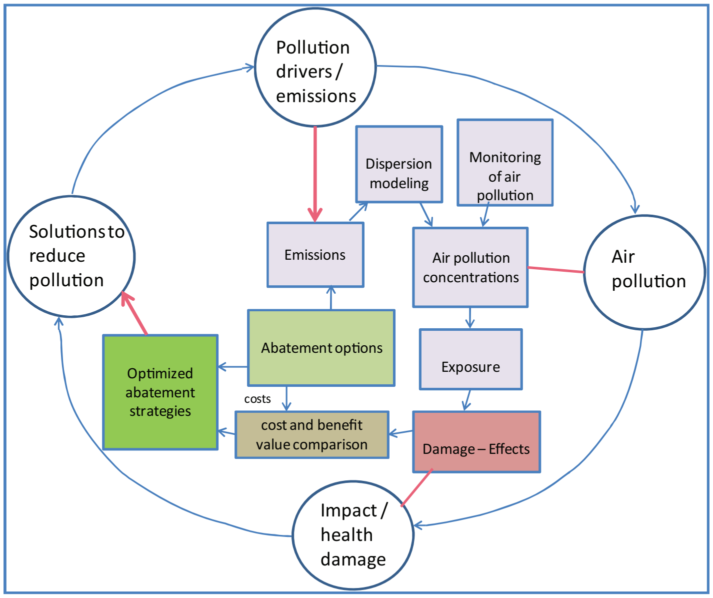
The AMHIB report provides analytical inputs for integrated air quality management. In addition to specific findings, based on available data, for current air pollution abatement strategy, its analysis should be replicated with updated and better quality data, as it becomes available and lessons learned are collected.

To some extent, the integrated air quality management concept contains many common-sense elements. To successfully combat urban air pollution in Ulaanbaatar, it is important to understand the characteristics of the various pollutants prevalent in the city, their sources, and their effects. This understanding is the basis for effective management of the air pollution problem.

Figure 2-1 illustrates the integrated air quality management concept. The outer circle shows how polluting activities—such as energy use, industrial activities, and transport—cause emissions that lead to polluted air, which in turn leads to adverse health effects. This emphasizes the need reduce the pollution, which usually reduces the emissions and hence improves air quality. The boxes inside the circle indicate how the analytical process finds the most effective solutions. These are linked to the outer circle through the starting point—the emissions—and through the end point—the solution strategies. In between these points, the analytical process undergoes monitoring data, modeling, health effects assessment, selection of abatement options. These are analyzed to find the most effective options in terms of comparison of control costs with reduced damage costs. *The continuous cycle of improvement is a key to success factor.* For example, spatial distribution

[4] The integrated air quality management concept is described in detail in the Urban Air Quality Management Strategy, Asia Guidebook: http://books.google.com/books?id=9G0c7d_nQcEC&pg=PA8&lpg=PA8&dq=urbair+guidebook&source=bl&ots=9pUtYHlKot&sig=ZlwtkH1m3KqY2OfO3AByz6Zatb0&hl=en&ei=B34SSu2SEI-ysgaus5mFDg&sa=X&oi=book_result&ct=result&resnum=1#PPP1,M1

Figure 2-1: General concept for development of cost-effective air quality management strategies



Source: Authors' illustration.

of ground-level air pollution (the pollution people are exposed to) must be overlaid with spatial distribution of the population. These two distributions can change for many reasons including, changes in weather, housing choices, increased/decreased mobility, migration, new sources of pollution, new and better quality data, etc. Thus, strategies that make sense today may need to be adjusted over time. Figure 2-2 provides further detailed illustration of how this general concept has been applied by this report.

Air quality assessment in Ulaanbaatar by the AMHIB monitoring program

The AMHIB air pollution baseline monitoring program in UB established eight monitoring stations for PM. Sites for the stations were selected on the basis of the following criteria: (a) use of existing sites and equipment operated by local environmental agencies and research institutes as much as possible; (b) monitor the PM near the local hospitals participating in the health study; and (c) cover the various areas in UB affected by different main sources. The program included monitoring of PM_{10} and $PM_{2.5}$ because both these fractions of PM are relevant as a basis for estimating the health effects of PM on the population. The time period for the monitoring covered a full year, from June 2008 to May 2009, in order to cover all the seasons and to provide the annual average concentrations needed for the health effects assessment. During the course of the AMHIB monitoring period, four additional monitoring stations were established through a donor program.[5] The data from this program provided additional basis for the PM assessment in UB. The PM monitoring programs are summarized in Chapter 3 and described in detail in Annex A.

There are large spatial variations in the PM concentration levels in UB as a result of the large spatial variations of the main PM emission sources. Although the spatial coverage of the monitoring network for each of the PM fractions (PM_{10} and $PM_{2.5}$) was limited the network was designed so that the large span of concentration levels across the city areas could be shown.

[5] Refurbished air quality monitoring stations were donated by Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ), an international enterprise for international cooperation.

Assessment of the spatial distribution of PM concentrations and the contributions from different emission sources

Two methods are available for estimating the contributions of the various main sources in UB to ground-level PM concentrations in different parts of the city.

The *receptor modeling approach* (or known as the "top-down" approach) collects monitoring data from air pollution monitoring stations and uses sophisticated filter analysis to determine the sources of pollution. For the AMHIB study, PM filters from three of the sites were used for this analysis. Methods, description, and results are summarized in Chapter 3 and in more detail in Annex B.

The *dispersion modeling approach* (known as the "bottom-up approach") builds on an emissions inventory (EI) of the main sources of air pollution. The EI data are used as input data to a dispersion model that, together with meteorological and other statistical data, can estimate the effects of sources on the hourly and thus daily and annual concentrations of major pollutants such as particulate matter (PM), SO_2, NO_X, ozone (0_3), and others. The dispersion model produces a map of the concentrations in the model area, giving their spatial distribution. In Ulaanbaatar the accuracy of the predictions of the model was evaluated by comparing the modeled results with the actual monitoring data from the PM monitoring stations. The dispersion model and its evaluation are described in Chapter 4 and in further detail in Annex C.

In the development of an emissions inventory for Ulaanbaatar, the basic methodology for estimating emissions from industrial or household fuel consumption, as well as traffic activity, used a standard formula regardless of emission type:

$$\text{Emissions} = \text{Activity} \times \text{Emission Factor}$$

For industrial or household sources with emission reduction and control technology such as scrubbers, electrostatic precipitators, desulfurization devices, the following equation was used:

$$\text{Emissions} = \text{Activity} \times \text{Emission Factor} \times (1 - \text{Efficiency in \%})$$

Emission factors for specific sources are either developed empirically through source testing or cited from publications by authorities such as the United States Environmental Protection Agency, the European Environment Agency, the International Energy Association, and accredited academic sources. The selection of good emission factors is crucial to compiling an accurate and dependable emissions inventory. Otherwise, an unreliable emission factor could translate into large discrepancies in the total emission estimates, and even larger discrepancies in the assessment of concentrations and contributions.

A preliminary emissions inventory for UB was first developed in 2007 (Guttikunda 2007). This inventory was updated in 2009 (World Bank 2009), and further updated—with improved population distribution data—in 2010 as part of the AMHIB study. The details of the previous emissions inventories are given in the references above, while the resulting inventory after the AMHIB updating is summarized in chapter 4 with more details in annex C. The methodologies used in the AMHIB data for UB have provided a basis for assessing the spatial distribution of PM contributions and the contributions from the different main sources.

Air pollution and population exposure assessment

In air pollution analysis worldwide, much attention is given to "population exposure", or the actual pollution concentration level that people are exposed to. It is important to assess the specific contributions of each key pollution source to population exposure—also known as the "source-sector-specific contribution to population exposure." This indicator reveals the importance of each source to the health effects of the population and is more meaningful than simply comparing gross emissions amounts per source, or even the average ground-level concentration

contributed by each source. The population exposure should ideally be calculated based upon data from each person's movements within the various parts of the city day-by-day, or even hour-by-hour. However, this detail of population exposure has not been carried out anywhere in the world and such data are also not available in Ulaanbaatar.

The assessment of population exposure in this report is constrained by the data available in Ulaanbaatar. Because pollution and people are unevenly distributed across the city, their exposure levels are different, depending on where they live and where and when they move about the city. The exposure of the population is summarized as one number, Population-weighted Exposure (PWE), which represents the whole population. The PWE sums up the average pollution concentrations within one km^2 cells on a distribution map (a grid of one km^2 cells covering the six central districts of UB) multiplied by the total number of people in each cell and divided by the total population. This PWE exposure number is based on the outdoor concentration in the grid cell where each individual lives, and does not, as mentioned above, take account of the difference in exposure that people are subjected to when moving outside their area and going to work and school, etc. A time-activity pattern would need to be established, which is unavailable. In UB this may be less important than in other cities, since the highest concentrations occur during early morning and late afternoon/evening hours when people tend to be mostly at home.

The PWEs are then used to calculate health effects (see following section).

The steps to assess the exposure and the effects of abatement of sources on the exposure are as follows:

1. Analysis of all available monitoring data. This gives an overview of the current air pollution problem, and it also provides a basis for evaluating the air pollution dispersion model.
2. Establish an emissions inventory, which includes all main sources including ger heating systems, heat-only-boilers, power plants, road traffic, soil suspension etc.
3. Establish air pollution modeling. A Eulerian grid model was used, which has embedded sub-grid models for calculation of pollutant concentrations resulting from different types of sources (area-, line- and point sources). The model solves the time-dependent advection/diffusion equation in a three-dimensional grid. The model grid used for the UB modeling is 30×30 km, and the grid cell size used is 1×1 km (see details in Annex C). Input to the model includes the emission inventory and meteorological and population data. The emissions are preprocessed to provide hourly emissions in each of the grid cells to the model.
   The model generates output hourly concentrations throughout the modeled period (for this report: one full year) in each of the grid cells, as well as in specific points, such as the locations of the monitoring stations
4. Calculate the annual average population-weighted exposure, total and contribution from each of the source categories, by combining the air pollution and population distributions in the grid.

Methods for health effects assessment

For this epidemiological analysis, a method similar to those of previous researchers was used to examine the relationship between daily exposure to air pollution and subsequent health effects. In these studies, statistical associations are determined between air pollution, including particulate matter, and several adverse health outcomes, including premature mortality (death) and hospital admissions for heart and lung diseases. The method, called "case-crossover," is similar to the case-control study often used in epidemiology. In this method, pollution on the date of the health event (case) is compared to pollution on several other reference days (controls) occurring within the same month and year. As a result, each individual in the study serves as his or her own control and there is matching on a wide range of individual-level characteristics. Thus, most factors that can impact

mortality, and which can also vary on a daily basis with air pollution, are implicitly taken into account by the study design.

This method significantly reduces the likelihood that some unmeasured factors will affect the results. By limiting cases and controls to the same month, factors that vary over a longer time scale (e.g., smoking, diet, exercise, age) will not change. Thus these factors will not have an impact on the statistical analysis. This method also allows for the examination of the impact of exposures that occur several days before the actual event. The basic analysis involves the full year of data collected in UB. However, given the large seasonal differences in concentrations and sources of particulate matter, additional analysis for mortality was conducted by dividing the year into cool and warm seasons. Ultimately, the study team determined the expected change in the health effect per every unit increase in the pollutant under investigation.

Methods for assessment of air-pollution-related health costs

Health impacts are estimated in physical and monetary terms in the following way:

First, a threshold value is set for annual average population-weighted exposure (PWE) below which no health risks are assumed. The threshold value chosen could be the guideline value set by WHO or other international guideline values or local standards. WHO guideline values are typically determined by the level of pollution concentrations that are identified in epidemiological studies as "threshold" levels for observable effects. Thus, they are a metric for the actual physical impacts rather than what may be defined as the target or acceptable level in a specific setting. For PM, there is no threshold level below which there are no effects. This study uses the annual average PM_{10} concentration of 15 µg/m^3 as the lower threshold level for the effects, as was done by WHO in the Global Burden of Disease assessment (Cohen et al. 2004).

Second, the PWE values are combined with estimated baseline rates of the given health end-point in the population and exposure-response functions. This gives the estimated health impacts of exposure to excessive levels of ambient concentrations of PM. The AMHIB study includes a time-series study using data from a broad range of hospitals in Ulaanbaatar to evaluate the exposure-response relationship between incidences of hospital admittances for various respiratory illnesses and cardiovascular diseases (CVD) and ambient concentrations of PM in the city (see Chapter 4). The results from that study are applied in terms of exposure-response functions for hospitalization, as well as for current hospitalization rates for respiratory and cardiovascular disease in Ulaanbaatar.

Third, a unit cost value is estimated for each health end-point. For premature deaths and chronic bronchitis, the study team relies on results from the survey on the WTP of Ulaanbaatar residents (see Chapter 5) to reduce risk of death associated with air pollution. Hospitalization cost estimates are transferred from a previous study in China (World Bank 2007).

Methods for assessment of costs of abatement options

Scenarios analyses were conducted to examine potential costs and PM_{10} reduction impacts of selected PM_{10} reductions measures. These scenarios include the following.

Baseline; business as usual
Scenario 1a: Reduce start-up emissions through backlighting the fire
Scenario 1b: Reduce start-up emissions through slight modifications of the stove
Scenario 2: Replace existing stoves with cleaner coal stoves, without changing the fuel
Scenario 3: Replace existing stoves and fuels with cleaner stoves and semi-coked Coal (SCC)
Scenario 4: Electric heating in existing ger homes
Scenario 5: Relocation of ger households into apartments
Scenario 6: Heat-only boilers
Scenarios 7 and 8: Fugitive dust (paving roads and greening the city).

In each alternative scenario, relative changes compared to the baseline scenario in terms of cost and PM_{10} reductions are examined. Detailed assumptions and methodologies are presented in Chapter 7 and Annex F.

The analytical scheme for cost-benefit evaluations

Figure 2-2 shows the more detailed analytical scheme followed in the work for this report. This is based upon the methodologies described above, and the air quality management concept shown in overview form in Figure 2-1.

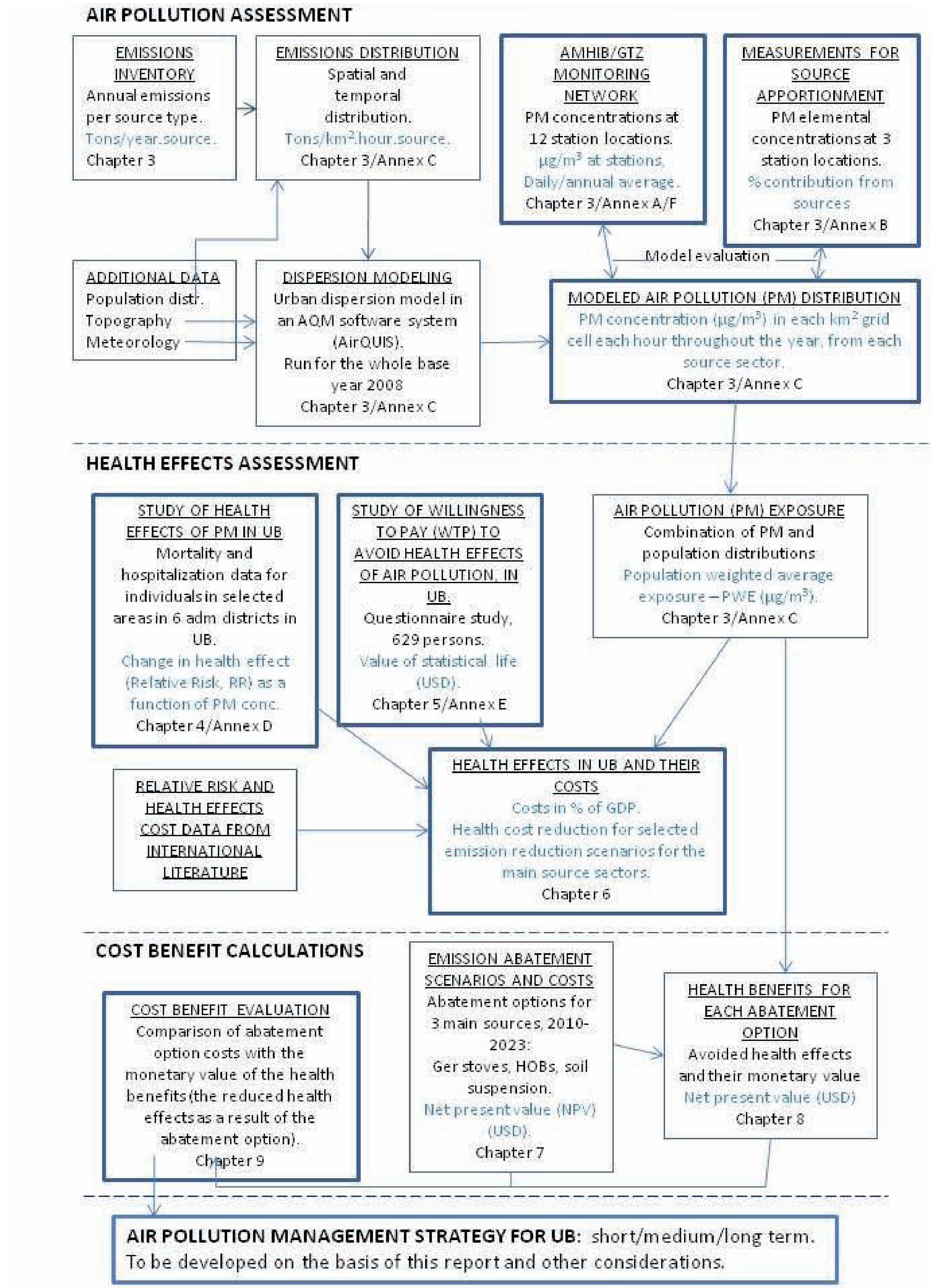
The analytical scheme has three parts.

1. *Air pollution assessment*. This includes the air pollution monitoring, emissions inventory, and the modeling (dispersion and receptor) activities. It also includes results in a modeled air pollution (PM) distribution (spatial and temporal) for the AMHIB year (June 2008–May 2009).
2. *Health effects assessment*. This includes the assessment of the population exposure (population weighted average exposure, PWE) and the studies on health effects and willingness-to-pay to avoid effects in Ulaanbaatar. It also includes results in an estimate of the costs of the health effects of PM in Ulaanbaatar, and their reduction for a selected set of emission reduction scenarios.
3. *Cost-benefit calculations*. This includes a study on pollution management scenarios and their costs for three main sources (ger stoves, soil suspension, heat-only boilers (HOBs), and the estimated health benefits and their monetary value for each option. The control scenarios cover a 15-year period, 2010–23. This also includes results in a cost-benefit evaluation, comparing the control costs with the value of the health benefit.

Figure 2-2 shows the type of values that are obtained from each of the studies and activities (each of the boxes in the figure), the relationship between them, and how the values are used in the analytical line.

A strategy for air pollution abatement in Ulaanbaatar can be developed on the basis of the cost-benefit evaluations of abatement options developed in this report, together with other considerations, such as the technical, economic, and political feasibility of the various options. An air pollution abatement strategy will typically be step-wise, with various options implemented in the short, medium, and long term.

Figure 2-2: Detailed analytical scheme to arrive at the cost-benefit evaluation



Source: Authors' illustration.

3. Assessment of the Present Air Pollution Exposure and Source Contributions in Ulaanbaatar

The objective of this chapter is to develop an estimate of the exposure of the population in Ulaanbaatar to particulate matter—the dominant air pollutant in UB affecting the health of its population.

The chapter explains the process of developing the exposure assessment, with references to Annexes A,B,C, and G, where the various parts are described in detail. Chapter 3 describes the monitoring program in UB under the AMHIB umbrella, and uses the these results to estimate the annual average PM concentration in the two main types of areas in UB—the ger areas and the central urban areas—based upon average and maximum measured concentrations. The PM concentrations are extremely high (see table 3-2), especially in the winter period. They are probably the highest in any capital city globally. In addition, the concentrations in the ger areas are much higher than in the central areas.

The chapter assesses the contributions to the PM concentrations from the various sources in UB. Two different methods were used. The first was based upon a combination of chemical and statistical analysis of PM samples taken over the year at three locations (called "source apportionment," or SA) through receptor modeling. The second was based upon dispersion modeling using emission inventories as its main input. The dispersion model was evaluated through comparison with the measured results, and with strong correlation between measured and modeled PM. There was also good agreement between the two SA methods, with both showing that the pollution originating from ger stoves and the pollution originating from suspension of soil dust are the largest contributors to PM pollution in UB, and together the two sources dominate PM concentrations.

The exposure of the population to PM was calculated by combining the spatial PM concentration distribution across the city and ger areas with the similar population distribution giving the "population weighted average exposure," or PWE. This is very high in Ulaanbaatar—about 430 μg/m^3 for PM_{10} and 260 μg/m^3 for $PM_{2.5}$—as an annual average for the AMHIB year (June 2008–May 2009). This average exposure is about 10 times higher than the Mongolian air quality standards, and 6–7 times higher than the most lax WHO target values (see box below). It should also be noted that, naturally, the average exposure value implies that about half the population is exposed to higher values than the average, and about half to lower values. The most highly exposed segment of the population experiences annual average concentrations more than two times the average exposure level. The population, especially in the ger areas, is exposed to extremely high daily PM levels, reaching several thousand μg/m^3 during many days of the winter.

The PWE results are used as an important input to the calculations of the health effects on the population, described in chapters 6 and 8.

The results of this mapping of PM concentrations in UB should have certain implications for the development of a long-term PM monitoring program in UB, not least that the ger areas should be covered with a number of modern air pollution monitoring stations.

Air Quality Standards and Guidelines for Particulate Matter (PM)

Air quality standards and guidelines are set to protect the public against risks of negative health impacts caused by the air pollution. The table below summarizes Mongolian air quality standards (AQS) as well as WHO guidelines, USEPA standards, and EU limit values (LV) for PM_{10} and $PM_{2.5}$.

WHO guidelines are the lowest. They represent the levels where effects are very small, and should be considered as goals for the future. WHO has established interim targets (IT-1-3), realizing that in many developing countries, the WHO guidelines cannot be met in the short term.

USEPA standards and EU limit values differ. The EU LV is stricter than the US AQS for PM_{10}, while it is more lax for $PM_{2.5}$. They represent to some extent what is politically and technically feasible.

Guidelines, Standards, Limit values (µg/m^3)				
	$PM_{2.5}$		**PM_{10}**	
	Annual average	24 hour average (daily)	Annual average	24 hour average (daily)
Mongolian Standards, 2007,MNS 4585:2007	25	50	50	100
WHO Guidelines, 2005	10	25	20	50
WHO Interim Targets (IT)				
IT-1	35	75	70	150
IT-2	25	50	50	100
IT-3	15	37.5	30	75
USEPA AQS, 2006	15	35 [1]	-	150
EU LV	25 [3] 20 [4]	-	40	50 [2]

1) 7 days above 35 per year is allowed (98th percentile)
2) 35 days above 50 per year is allowed (90th percentile)
3) To be met by 2010
4) To be met by 2020
[1]*Source:* WHO 2005.

Assessment of air pollution concentrations by monitoring

Monitoring program

It has been established that particulate matter (PM) constitutes the dominant air pollution problem contributing to health effects on the population in Ulaanbaatar (World Bank 2009). As a result, the AMHIB monitoring program concentrates exclusively on monitoring PM concentrations. The program includes PM_{10} and $PM_{2.5}$, the two fraction sizes of PM in air that are most relevant for the evaluation of the health effects of PM. It has also been established that PM concentrations are much higher in the areas dominated by traditional households (the ger areas) than in the central parts of the cities dominated by apartment houses, as well as more modern single-family houses. Thus, a PM monitoring program has to cover both the central areas of the city, as well as ger areas.

Monitoring sites for the AMHIB project are shown in Figure 3-1. They were selected based upon the knowledge of the spatial air pollution distribution in Ulaanbaatar using data from stationary monitoring stations that existed

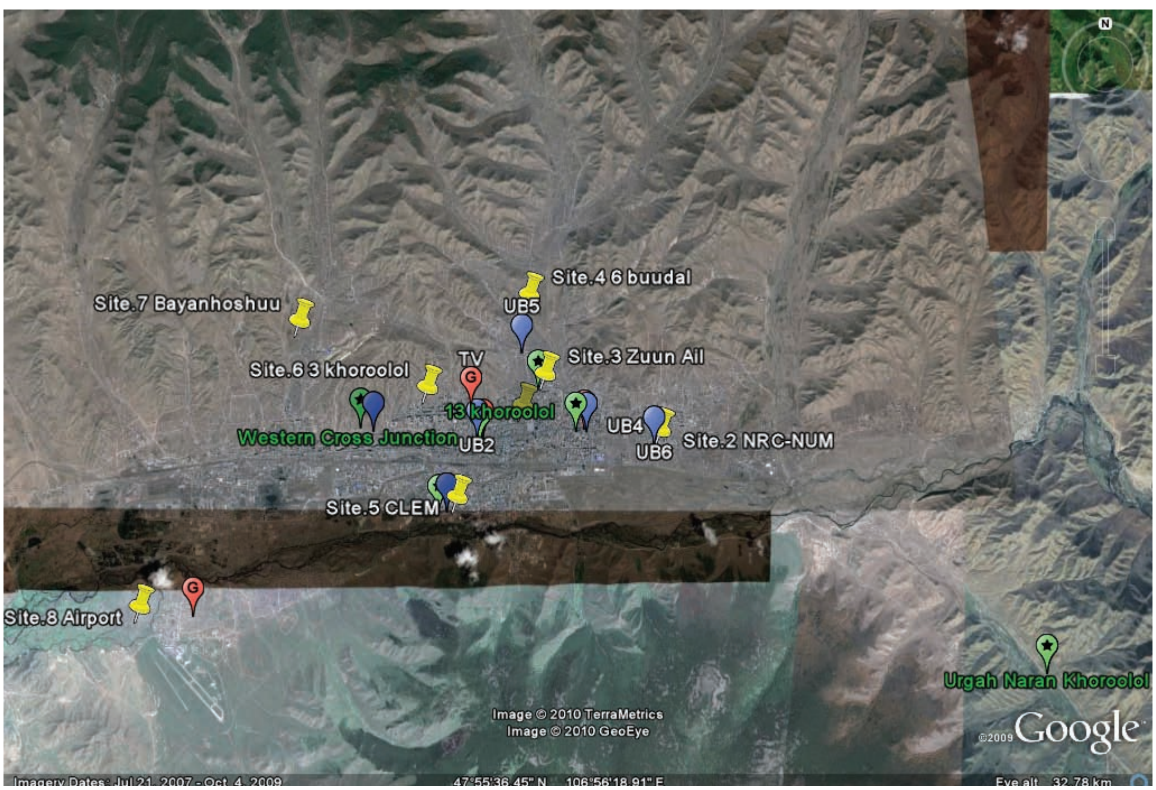
prior to the start of the AMHIB (operated by NAMHEM, CLEM-NAMHEM, NRC-NUM); the geography and topography of UB; population density representations; and the locations of family hospitals participating in the health study part of the project. Before the AMHIB monitoring started, PM measurements had already been conducted for a short period at the CLEM station (PM_{10}), at the NAMHEM site ($PM_{2.5}$ and PM_{10}), and at the NRC site ($PM_{2.5}$ and PM_{10}). The other sites (3, 4, 6, 7, and 8) were chosen because they were near the participating family hospitals. The stations were located such that they represent the general air pollution level in the surrounding area, and were not affected significantly by any one single nearby source. Stations 3, 4, 6, 7, and 8 are located in the more polluted ger areas, while 1, 2, and 5 are in more centrally located populated areas. PM_{10} was measured at stations no. 1, 2 (central areas), and at 3, 5, and 6 (ger areas). $PM_{2.5}$ was measured at stations 1, 2 (central), and at 3, 4, 7, and 8 (ger areas).

The measurement program ran from June 1, 2008, to May 31, 2009. Measurements were carried out two days per week (24 hour sampling on Wednesdays and Sundays). In addition, from October to April measurements were carried out every day during one week per month.

In addition to the AMHIB stations, four stations provided by a German donor and operated by GTZ (now known as GIZ)[6] came into operation in January 2009, using automatic monitoring equipment. Two of the stations were located near traffic crossings/ streets (termed "Western" and "Eastern Cross" in figure 3-1). The TV station location is near a ger area, while the airport station is located in a fairly clear area near the airport. The data from the MUB station provides important additional

[6] The GTZ-funded and originally GTZ-operated monitoring stations (MS) have been transferred to the Urban Air Quality Department of the Ulaanbaatar Municipality (MUB), now referred to as "MUB stations".

Figure 3-1: Location of AMHIB (yellow), MUB (red), and French (green) sampling sites in Ulaanbaatar



Note: Blue points mark meteorological stations.
Source: Authors' illustration.

insight that supports the conclusions regarding the PM assessment from the AMHIB stations, as well as regarding the importance of the various source categories in the different areas of Ulaanbaatar.

Annex A provides details about the monitoring program, the stations, the resulting monitoring data, and an assessment of their quality. The annex includes a detailed presentation and visualization of the main features of PM air pollution in Ulaanbaatar. A summary of the results is provided as follows.

Measurement equipment at the AMHIB stations varied, depending upon which equipment was already available from the different agencies involved in the AMHIB monitoring. The data quality assessment, partly based upon parallel sampling with all equipment at the same place carried out during three different weeks, revealed sampling artifacts and problems with most of the samplers (see annex A). The data from the parallel sampling, together with additional information, gave a basis for adjusting the output from some of the instruments and a final assessment of the PM concentrations at the AMHIB stations (see annex G).

Measured PM concentrations and their variability in Ulaanbaatar, June 08–May 09

The most significant feature of PM levels in UB is the very strong seasonal variation, with extremely high concentrations during the winter period, from November to March, as shown in figure 3-2. The ger area stations have much higher concentrations than the NRC station, which is located near, but shielded from ger area emissions by houses. This is almost certainly caused by extensive coal burning for heat and power generation during the cold season, although suspension of dry soil dust is also a significant PM source in UB. Figures 3-4 and 3-5 show the episodic nature of the PM pollution, with extremely high concentrations on some days, especially in the winter. Very high daily episodes are typically due to a particular type of meteorological conditions, typically very cold days with low winds and ground-level inversion trapping the pollution emitted at low heights within a shallow layer of air near the ground. The very high concentrations measured on some days at individual monitoring stations (as shown in the example figures 3-4 and 3-5 below) can represent as much as 50-100 μg/m^3, or up to about 25% of the annual average concentrations at some stations and are thus important for determining the annual PM pollution level.[7]

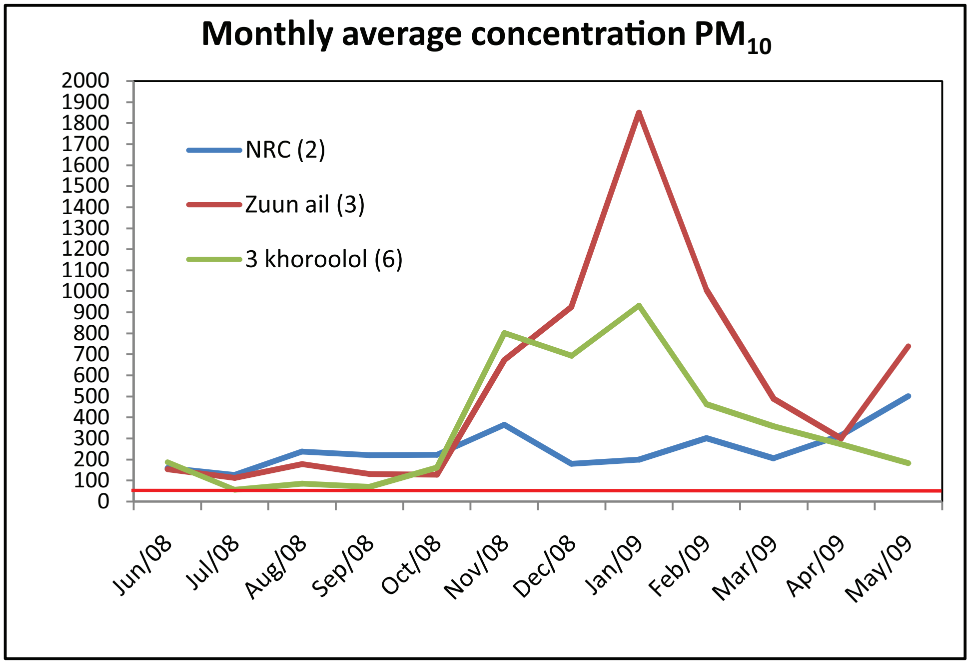
Figures 3-2 to 3-5 show the different typical PM pollution features at different stations representing the two different types of areas. At station 6 within the ger areas, the seasonal variation and episodic peaks are much more pronounced than at the NRC station outside the ger areas.

Figure 3-6 and 3-7 show the annual average PM concentrations as measured at the AMHIB stations. The relevant air quality standards (AQS) are indicated in the figure (as also in figures 3-2–3-5). This shows clearly that the PM concentrations in Ulaanbaatar during the AMHIB measurement period far exceed Mongolia's own AQSs. The concentrations were also much higher than the most moderate WHO interim targets for PM_{10} (70 μg/m^3) and $PM_{2.5}$ (35 μg/m^3). The annual average PM_{10} concentration at the most affected station was more than 10 times higher than the Mongolian AQS, while the annual average $PM_{2.5}$ concentration at the most affected station was more than 25 times higher.

It should be noted that the $PM_{2.5}$ and PM_{10} levels measured at the stations cannot be directly compared, as they are not measured at the same sites in general, and some of the $PM_{2.5}$ stations are located in more polluted areas than some of the PM_{10} stations.

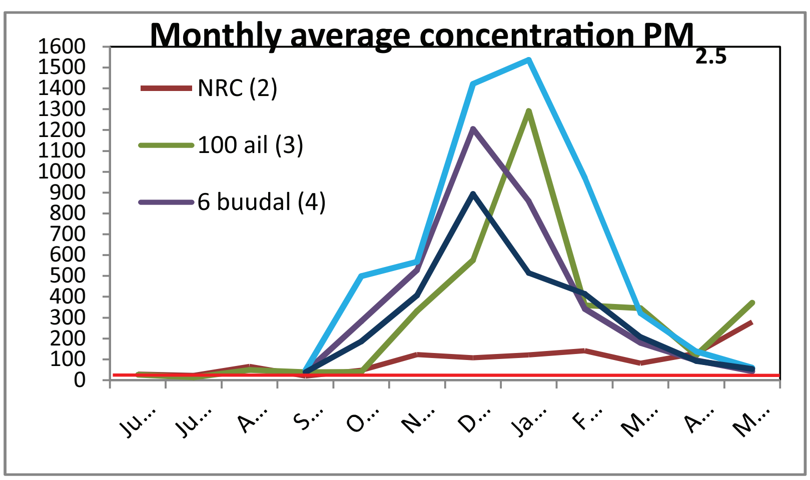
7 No specific reasons have been found to reject these measurements. Although errors cannot be ruled out, they are regarded as examples of the very high exposures to PM that can occur due to a combination of very large emissions at low heights locally near the stations and adverse dispersion conditions.

Figure 3-2: Monthly average concentrations of PM_{10} in Ulaanbaatar, June 2008–May 2009



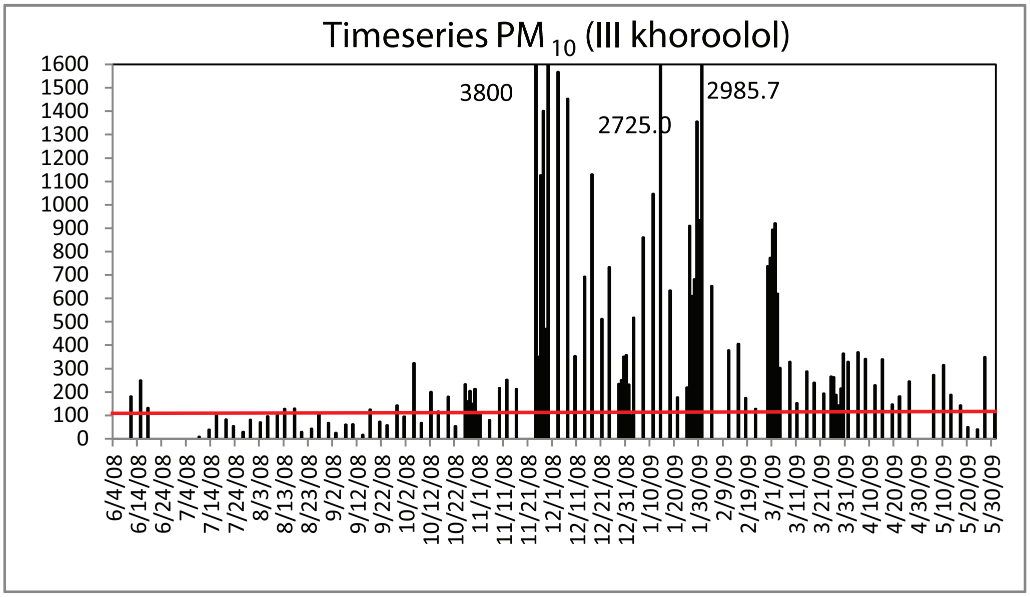
Note: Red line in Figure shows the Mongolian Air Quality Standard.
Source: Authors' illustration based on AMHIB monitoring.

Figure 3-3: Monthly average concentrations of $PM_{2.5}$ in Ulaanbaatar, June 2008–May 2009



Note: Red line in Figure shows the Mongolian Air Quality Standard.
Source: Authors' illustration based on AMHIB monitoring.

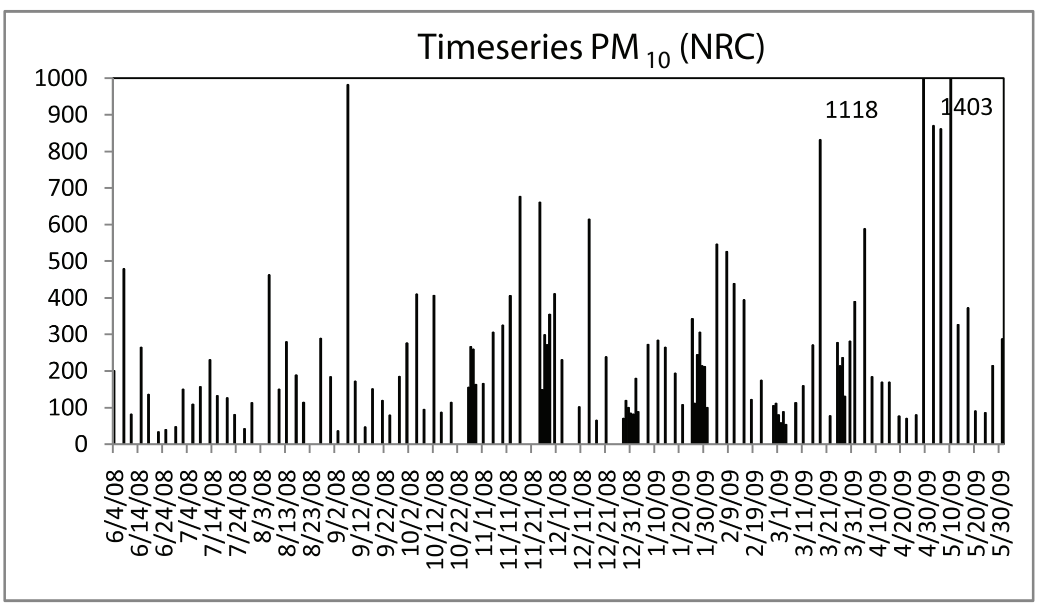
Figure 3-4: Examples of individual daily measured concentrations at station 6 (3 Kholoolol, in ger area)



Four peaks in the range 2,725-3,800 µg /m³ extend above the top of the vertical axis.

Source: Authors' illustration based on AMHIB monitoring.

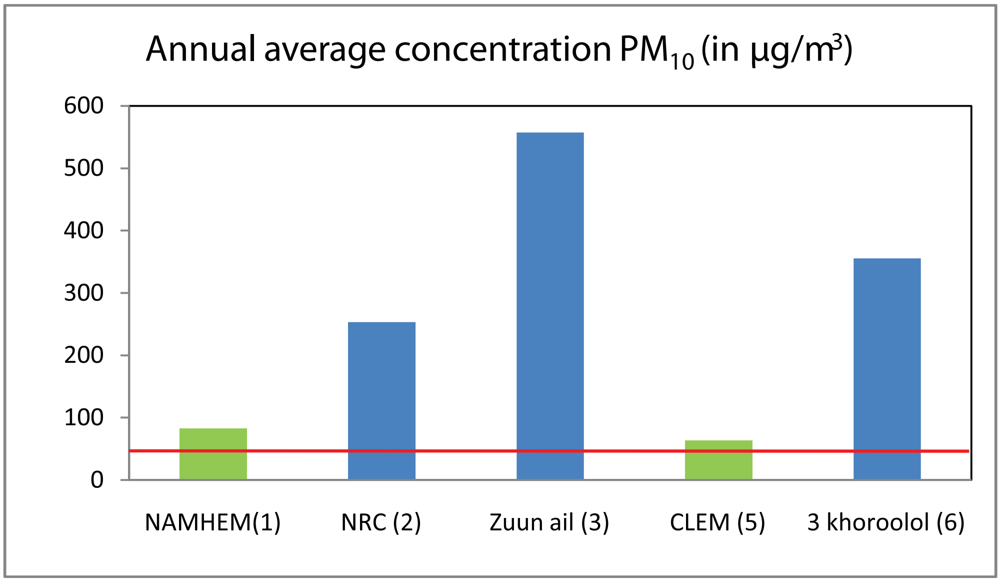
Figure 3-5: Examples of individual daily measured concentrations at station 2 (NRC, East of city center, outside ger areas)



Two peaks of 1,118 and 1,403 µg /m³ extend above the top of the vertical axis.

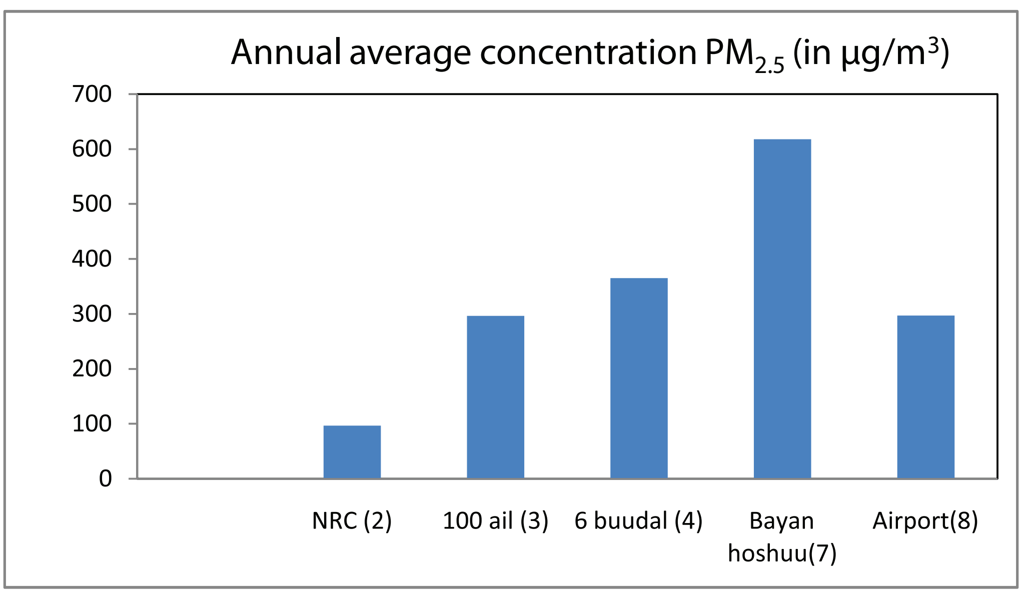
Source: Authors' illustration based on AMHIB monitoring.

Figure 3-6: Annual average PM_{10} concentrations as measured at AMHIB stations in Ulaanbaatar, June 2008–May 2009



Note: The instruments at stations 1 and 5 measure too low concentrations, and are thus indicated with a different color in the figure.
Source: Authors' illustration based on AMHIB monitoring.

Figure 3-7: Annual average $PM_{2.5}$ concentrations as measured at AMHIB stations in Ulaanbaatar, June 2008–May 2009



Note: The instrument at stations 4, 7 and 8 measure exceptionally higher concentrations during the winter months, due to influence from high relative humidity.
Source: Authors' illustration based on AMHIB monitoring.

Figures 3-2–3-7 present the concentrations measured by the various equipment. The data quality assessment based upon inter-comparison between the various instruments revealed sampling artifacts and problems with most of the samplers (see annex A). Data correction procedures were developed based upon the inter-comparisons and other information.

Applying these corrections to the measured concentrations gives the corrected PM concentrations presented in table 3-1. The uncertainty of the corrected numbers is indicated with indices 1–3, with 1 being the least uncertain and 3 the most uncertain. Statistics for quantifying the degree of uncertainty are not available. It is judged it to be of the order of ±10–15 percent for index 1, ± 15–20 percent for index 2, and ± 40–50 percent for index 3.

Compared to the data from other cities in global data bases, Ulaanbaatar could be the most PM polluted capital in the world, with higher concentrations than in Chinese cities. Figure 3-8 shows examples of PM concentrations in other highly polluted cities (World Bank 2009).

Summary of PM levels in Ulaanbaatar

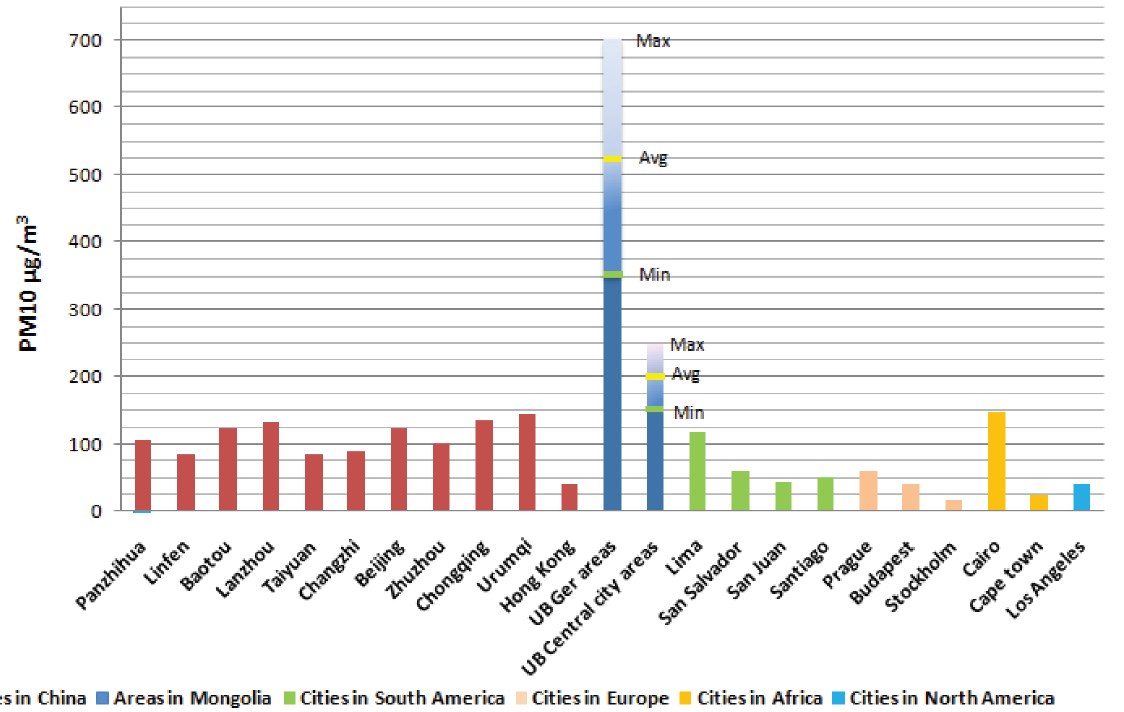
The UB data show the large difference in concentration between the AMHIB ger area stations and the NRC station outside the ger areas. The GTZ stations provide additional data. They are located mostly outside the ger areas, in central UB locations as well as in a thinly populated ger area near the airport. The GTZ station at the TV antenna is different, although it is located near ger areas. The concentrations reported for the MUB stations are significantly lower than the AMHIB ger area concentrations (see annex A, table A.6). It is not possible simply from the measurements at the stations to establish an average overall PM concentration number for Ulaanbaatar. Air pollution modeling is required to achieve that. However, from the measurements the annual average concentration levels in the two types of areas, the ger areas and the central UB areas, can be indicated separately. The line of reasoning is described in chapter A5 in annex A. Table 3-2 shows the result of this assessment. The results from the PM measurements at the four MUB stations that provided data for the period December 2008–May 2009 confirm the ranges indicated in table 3-2.

Table 3-1: Annual average PM concentration of Ulaanbaatar city, corrected according to results from sampler comparisons

Site No	Site name	$PM_{2.5}$	PM_{10}
2	Nuclear Research Center	78 [3]	253 [1]
3	Zuun ail	236 [3]	558 [1]
4	6 Buudal	225 [2]	
6	III Khoroolol		>700 [3]
7	Bayankhoshuu	338 [2]	
8	Airport	190 [2]	
1	NAMHEM	59 [4]	76 [4]
5	CLEM		67 [4]

Note: Indexes 1-3 indicate the uncertainty of the numbers, with 1 the least uncertain and 3 the most uncertain. Index 4: The instruments at these stations were shown to give too low values. They are included here for completeness.
Source: AMHIB data.

Figure 3-8: Comparison of UB PM_{10} concentrations (2008–09) with Chinese cities (2008) and other capitals in the world (2004)



Source: Authors' illustration based on data from the China Environment Yearbook 2009 for Chinese cities, AMHIB study for UB, and WHO Air Quality Guidelines - Global Update 2005 for other cities.

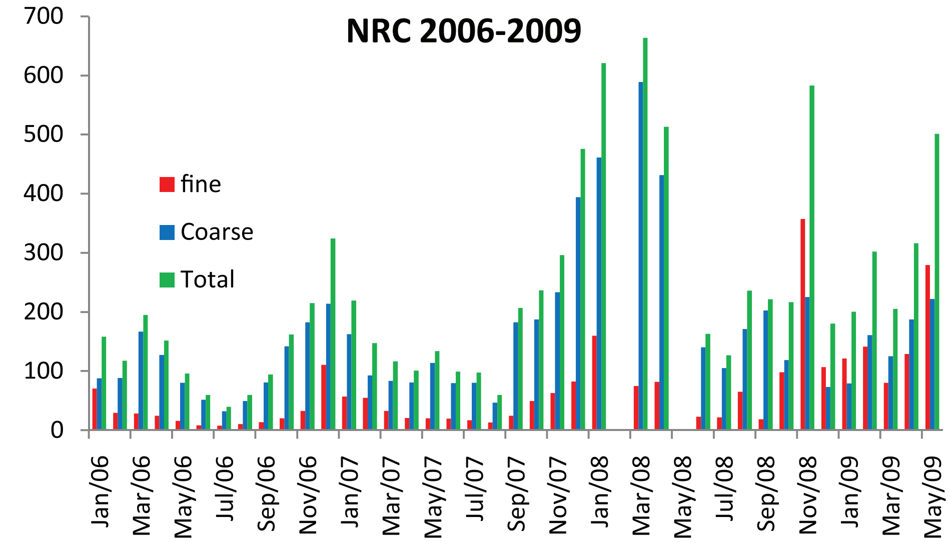
Table 3.2: Indicated ranges for annual average PM concentrations in Ulaanbaatar, June 08-May 09, linked to the areas where the measurements were carried out

Area	PM_{10} µg/m^3	$PM_{2.5}$ µg/m^3	Exceedance: Ratio to AQSs	
			Mongolian:	WHO
Central city areas	150–250	75–150	3–6	7–15
Ger areas	350–700	200–350	7–14	17–35

Note: These indicated PM levels represent the situation in the AMHIB period, June 2008-May 2009. They are linked to the areas where the measurements were carried out. They do not cover all polluted areas in Ulaanbaatar.
Source: AMHIB data.

PM has been measured at the NRC station since 2006. Figure 3-9 shows monthly time series of PM concentration at the NRC site (AMHIB site 2) for 2006–09. This time series shows a trend toward increased concentrations over the period, both during the summer and winter. The highest winter concentrations of PM_{10} occurred during winter 2007–08, while concentrations during the last (AMHIB) winter were also higher than in the first two winters of measuring. For $PM_{2.5}$, the highest levels were measured during the last winter, and these were significantly higher than in earlier years. Possible explanations are increased polluting activities resulting in higher emissions and/or in changes in meteorological conditions.

Figure 3-9: PM10 (total), $PM_{10-2.5}$ (coarse), and $PM_{2.5}$ (fine) concentrations at the NRC station (AMHIB site 2) for 2006–09



Source: National University of Mongolia and authors illustration based on AMHIB monitoring Contributions to PM concentrations from main emissions sources.

The main sources of PM concentrations in Ulaanbaatar have previously been assessed as emissions from the burning of coal and wood for heating of individual residences in ger areas (ger stoves) and suspension of dry dust from roads and other surfaces (World Bank 2009). Emissions from power plants, heat-only boilers (HOB), and car and vehicle exhaust are also important sources, although they were assessed as smaller contributors to ground-level PM concentrations.

The elemental analysis of sampled PM on filters from the AMHIB stations supported the dominance of coal combustion and suspended soil particles.

An additional supporting indication of the extent of contributions from main sources can be extracted from the AMHIB and MUB measurements. Starting with the PM situation in central UB areas, the hourly measurements of PM_{10} and $PM_{2.5}$ at the MUB station "Western Cross" can be used as a descriptive illustration (see figure 3-10).

$PM_{2.5}$ concentrations during summer (given as June in the figure) represent the contribution from vehicle exhaust near the heavily trafficked road crossing. At that time of the year, concentrations from ger heating sources and other combustion sources (except the power plants) are very low. Concentrations during the morning hours, as well as during the afternoon rush hour and evening hours, are increased, although this is not very apparent in the scale used in figure 3-10. This increase is the result of the combined influences of the typical daily wind speed variation (increased day-time wind speed), the daily variation in traffic volume with rush hours, as well as a small influence from evening cooking in gers. These variations and source influences are very small compared to the very much higher winter time concentrations. The winter curves show strong morning and evening increases at the Western Cross station, which is located in a central UB area but fairly close to ger areas to its north and west. The periods of increase correspond with periods of ger heating. The prolonged evening/night peaks can be partly explained by the normally reduced wind speed at night, combined with often strong ground-level temperature inversions causing reduced dispersion and increased concentrations. In addition, the afternoon traffic rush hours

are not as pronounced in the winter months indicating that the vehicle exhaust contribution to the $PM_{2.5}$ concentrations is limited when compared to other sources, even at this traffic-exposed site.

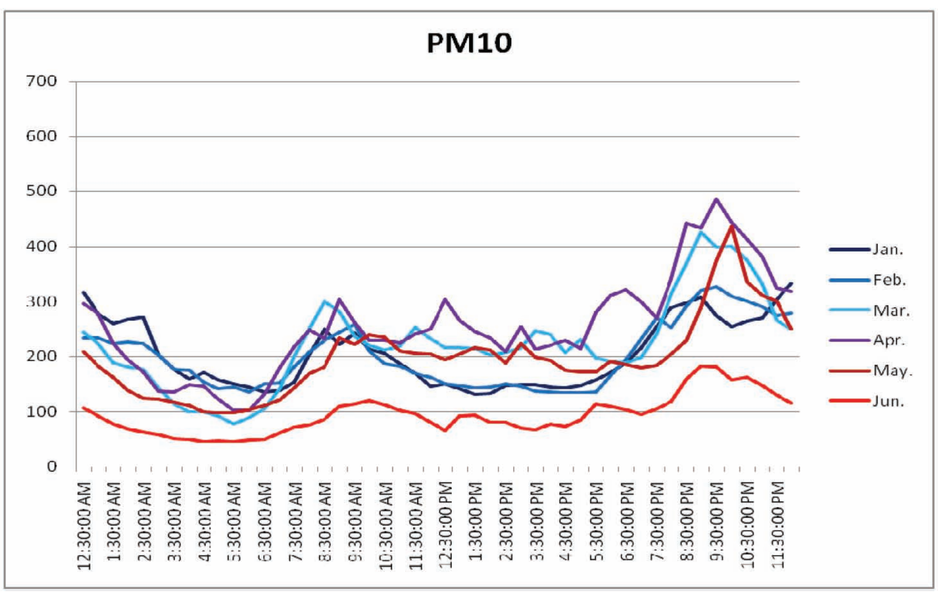
The much higher PM_{10} concentrations indicate a large influence from sources of the coarse PM fraction (particle sizes between 2.5 and 10 micrometer) even in the summer (June). Sources of coarse PM are suspension of dry dust from surfaces, such as open dry ground, as well as roads and their surroundings. The combustion of coal and wood in gers and other combustion sources also contribute to some extent to coarse PM. The average daily variation shown in figure 3-10—increases significantly in the morning, increases slightly less during mid-day, and has a strong evening peak—indicating that road dust and other coarse PM sources are involved. The coarse fraction is especially large during spring time (March–May) providing a clear indication that suspension of dust from dry surfaces (open soil surfaces and roads) is an important source.

A similar analysis from the MUB TV station located close to ger areas shows similar variations to the Western Cross station, although these are more pronounced, indicating the importance of ger area emissions (see annex A, figure A.31).

The measurements presented in this sub-chapter indicate that ger heating sources are a major contributor to $PM_{2.5}$ concentrations in the ger areas. This also contributes to PM in the central areas of UB. Dust suspension from open soil surfaces and roads is another major source of coarse PM. The influence from road vehicle exhaust is limited, even in central traffic areas. The contribution from power plants and HOBs to PM concentrations in UB cannot be quantified by means of the data presented in this section.

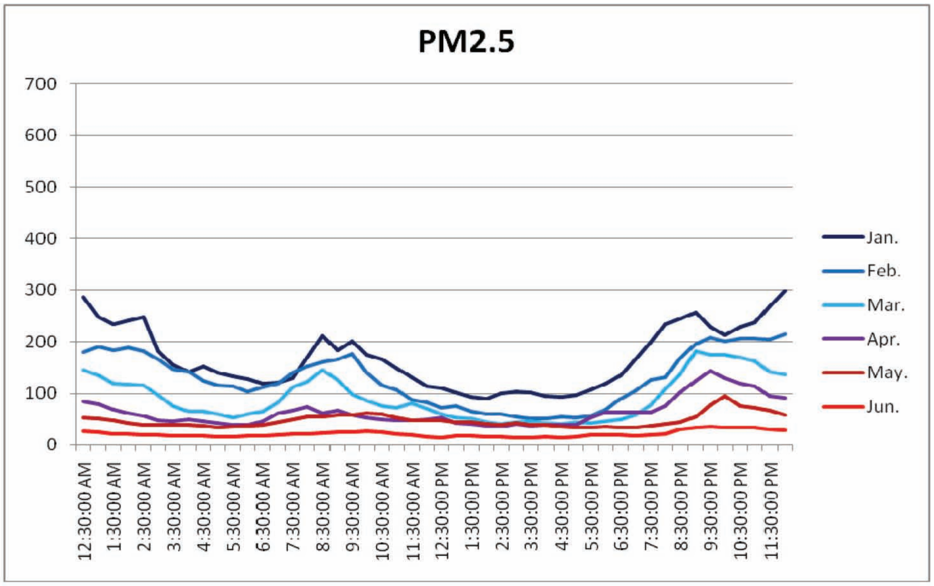
Such evaluations, based upon analysis of measured time series, can only be used as an indication of PM source contributions and their importance. Quantitative analysis for source contributions are described in the following sections.

Figure 3-10: Monthly averaged daily variation of PM_{10} and $PM_{2.5}$ at the MUB Western Cross Station during work days



continued

Figure 3-10 *continued*



Source: Authors' illustration based on AMHIB monitoring.

Ger stove firing practices and variability in the PM concentrations in Ulaanbaatar

Hourly measurements of PM show typical daily variations that correlate with the daily routine firing practices of the typical ger stove. Figure 3-11 shows, as a typical example, PM hourly concentrations on November 19–20 at the Takhilt meteorological site (Meteo site no. 3) in a ger area to the west of UB center. Clear peaks are shown in the morning (the right-most peak in the figure) and two-three successive peaks in the afternoon/evening. These correspond with ger stove firing periods. The evening peak is longer, corresponding to prolonged firing, while the morning firing is shorter, for heating and cooking before going to work. The evening peaks correspond to stove loadings.

It is notable that smoke pollution tends to be higher in December early in the winter than later (see figure A.36 and figure A.37 in annex A). This occurred despite the daily average temperature being slightly in lower in January 2009 than December 2008. This could be because at the beginning of the winter people keep the stoves cold, and fire them two or more times a day. This makes more pollution than when the stoves are kept hotter throughout the day and night as is the practice in the colder mid- and late winter.

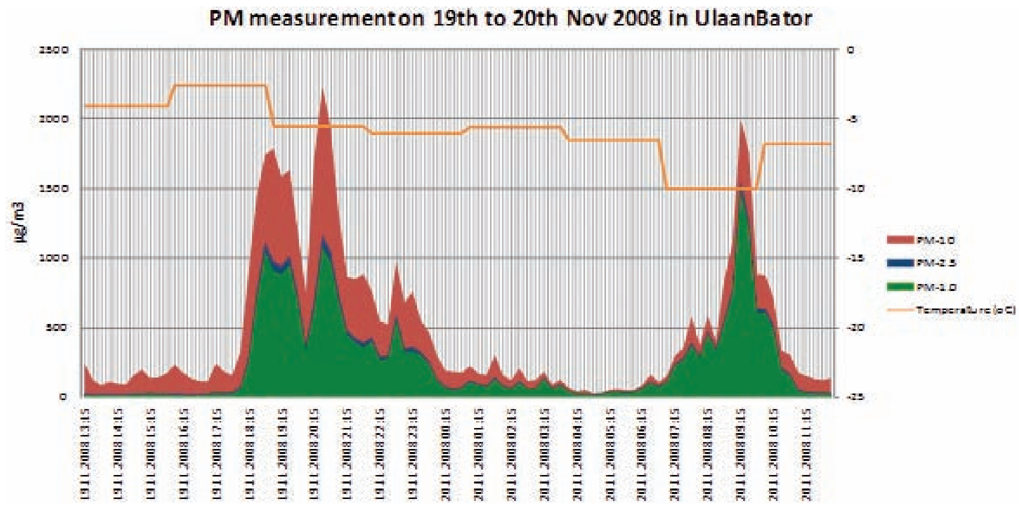
By an approximate calculation, about 50 percent of PM concentrations corresponds to the morning ignition phase (cold start) (8.30–9.30), the evening phase (18.30–19.30), and during the reloading of stoves (20.30–21.30).

Quantification of contributions to PM air pollution from various source categories

Emission inventory

The amount of emissions from the various source categories provides an initial estimate of their contribution to air pollution in an area. The emissions inventory presented in table 3-3 is based upon a preliminary inventory prepared for the World Bank in 2007 (Guttikunda 2007), updated in 2008–2009 (World Bank 2009) and further updated in the preparation of this final report. The inventory shows that ger households are the largest source of PM emissions in total, while power plants (CHP) and road dust suspension also contribute large amounts of emissions. The CHP emissions used here are based upon emission measurements carried out by

Figure 3-11: Example of time series of PM for one day at the beginning of winter, at Takhilt meteorological site, November 19–20, 2008



Note: Measurement using a GRIMM 107 PM monitor.
Source: Authors' illustration based on AMHIB monitoring.

Table 3-3: Summary of the emissions inventory for Ulaanbaatar, 2008 (tons/year)

Source	PM_{10}	$PM_{2.5}$	SO_2	Height of emissions, meters	Spatial distribution
Ger households	19,731	15,785	8,784	3–5	Throughout ger areas
HOBs	1,077	646	4,360	10–20	Dispersed over UB surroundings
CHPs	18,589	7,436	33,600	100–200	3 point sources to the west of UB center
Vehicle exhaust	1,161	1,161	1,354	<1	Dispersed along main road system mainly throughout the central city areas
Dry dust from roads					
Paved	5,142	771		<1	Mainly throughout the central city areas
Unpaved	4,812	722		<1	Mainly throughout the ger areas

Source: AMHIB data.

JICA (see annex C, which includes an uncertainty evaluation). It is important to note that soil dust suspension from surfaces other than roads is not included in this overview of emissions, although it is included as a source in the air pollution modeling.

Contributions to ground-level concentrations

Table 3-3 also shows the height of the source emission points and their spatial distribution. The higher the emission point, the lower tends

to be the general contribution from the source to ground-level concentrations, due to the increased dispersion of the emissions before it reaches the ground. Thus, the contribution of the CHPs to ground-level concentrations is much less than indicated by the emission amount in the table. The spatial distribution of emissions is obviously also important, and causes the source contributions to vary across different areas of the city. The large amount of emissions from the ger areas at a low emission height, dispersed and at the same time concentrated among the population in the Ger areas, account for a potentially significant contribution in those areas. Road dust and vehicle exhaust account for a significant contribution in the areas with large amounts of traffic. The contribution from HOBs can be significant near and downwind of areas with many HOB stacks. This is also the case for power plant emissions, although it is limited due to the height of their stacks.

Assessment of the source contributions to ground-level concentrations can be carried out using one of the following two methods:

- Source apportionment of PM sources through *receptor modeling*. This method requires extensive analysis of a large number of PM samples collected on filters. The AMHIB data collection provided the basis for such an analysis. This method provides estimates of source contributions at the sites where the samples were taken.
- Source apportionment through *dispersion modeling*. This requires an emission inventory, meteorological and other data, and a tested dispersion model evaluated for the area. This method can potentially assess the contributions spatially throughout the modeling area.

Results from receptor modeling of source contributions are given in the sections immediately below. Results from dispersion modeling on average source contributions and its spatial variation are given in the last section of this chapter.

Source apportionment by receptor modeling from AMHIB data analysis

Samples and methods

The samples collected at three AMHIB sites were used for the analysis: (1) NRC (site 2); (2) Zuun Ail (site 3), where two fractions, $PM_{2.5}$ (fine) and $PM_{10\text{-}2.5}$ (coarse) were collected; and (3) at III Khoroolol (site 6) where only one fraction, PM_{10} was collected. Figure 3-1 shows their location. The three sites represent different locations and positions relative to main PM sources in UB, and thus give a degree of spatial understanding of the source contributions to PM in the air:

- Site 2, NRC, is located a few kilometers to the east of central UB away from the main ger areas and main roads, in an area with open soil surfaces in the neighborhood. It is expected that the soil sources will contribute significantly to this site.
- Site 3, Zuun Ail, is located a few kilometers northeast of central UB, near small valleys to the north (Chingeltei, Hailaast, and Selbe). Extensive ger areas are located in those valleys to the north and expose the site to emissions from ger heating systems when air flows down the valleys toward the south. Few open soil surfaces surround the site, and the site is also removed from the main roads, although there are unpaved roads with light traffic. Sampling height at the site 3 is at 6m, which might slightly reduce the influence of local dust re-suspension. It is expected that ger area emissions will contribute significantly to this site.
- Site 6, III Khoroolol, is located well within a ger area surrounded by local unpaved roads. The sampler was placed at a height of 4m height on a balcony on the second floor of a residential house. Again, ger area emissions along with soil and unpaved road dust, are expected to contribute significantly to this site.

A total of 545 particulate matter samples were included in the receptor modeling analyses of AMHIB data, from June 2008 to May 2009.

Annex B gives details on the methods, analysis, and results from the receptor modeling. A summary is provided below.

Identification of PM sources

Output from the statistical analysis, using the Positive Matrix Factorization method (PMF) (see annex B), identifies a number of "factors" which are defined by their specific and separate element composition, or profile. From this elemental profile, it is often possible to allocate the "factor" to a certain pollution source, based upon knowledge of tracer elements or the elemental composition of the emissions from the source type. From the statistical analysis of the AMHIB data, it was possible to allocate factors to sources associated with coal combustion, motor vehicles, road dust, and soil.

The following sources could be identified through the factors derived from the PMF analysis:

Soil: Airborne soil originates from crustal matter. It has been possible to identify two different sources of airborne soil in UB: (i) a source identified by soil elements (named Soil 1) and (ii) a Soil 2 source with a significantly higher black carbon (BC) component. The difference between the two crustal matter sources is most likely the location, with the Soil 2 source originating more locally in Ulaanbaatar, where there is likely to be a greater concentration of settled combustion particles and coal dusts mixed into the crustal matter, hence the higher presence of BC in the source profile. Soil 1 is likely to represent the general crustal matter in the area around Ulaanbaatar. The soil sources contribute to PM in air through the well-known action of wind and turbulence to suspend the particles in the soil surface in the air. The soil sources in UB contribute mostly to the coarse PM fraction ($PM_{10-2.5}$), but it also accounts for a significant portion of the fine PM fraction ($PM_{2.5}$). The very dry and cold climate in Mongolia probably causes a distribution of the top-soil particles consisting of a higher fraction of very fine particles, compared to areas with more humid and mild climates.

Combustion: In some cases, it has been possible to identify two distinct combustion source types with differing combustion characteristics. One contains black carbon and a significant sulfur component (called Combustion 1); while the other also has black carbon, but with relatively lower sulfur content and higher soil elements (called Combustion 2). The high-sulfur profile could be associated with high-temperature coal combustion (such as in power plants and boilers), while the low-sulfur could be associated with low-temperature combustion, such as in small-scale residential stoves. The combustion sources contribute mostly to the fine PM fraction ($PM_{2.5}$), while they also have smaller contributions to the coarse PM fraction.

Motor vehicles/road traffic: The profile associated with a local motor vehicle and road dust component contains BC, zinc, and lead, along with elements typical of crustal matter. Mongolia has recently phased out leaded petrol, although there is likely to be residual lead in local road dust. This is a mixed profile consisting of exhaust particles in the fine fraction ($PM_{2.5}$) and suspended road dust in the coarse PM fraction ($PM_{10-2.5}$). These two parts of the profile are highly correlated in time since they both originate from road traffic with its specific time variation, and thus they appear in the analysis as one source.

Biomass burning: The profile associated with biomass burning contains black carbon and potassium in the samples. In UB, biomass burning contributes mostly to the fine PM fraction ($PM_{2.5}$).

These profiles/sources contribute differently to the coarse and fine fractions of PM at the various sites.

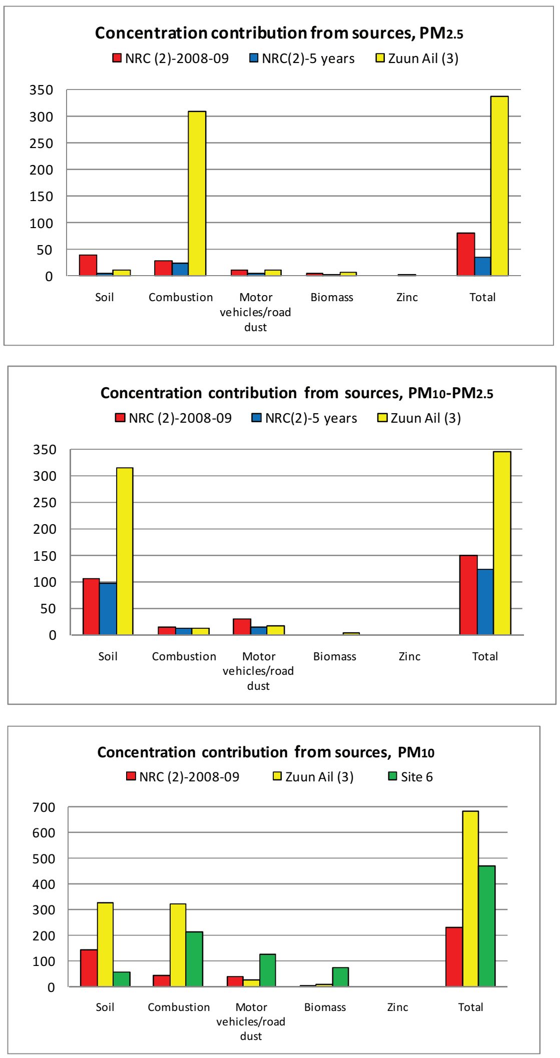
Results of the source apportionment using the PMF method

Contributions from the various sources were calculated for the three sites (NRC, Zuun Ail, and III Khoroolol). For the NRC site, a five-year data series (2004–09) was also available, and source apportionment (SA) analysis was also carried out for this five-year period.

The SA results are summarized in figures 3-12 and 3-13.

This indicates that the ***combustion source*** is the largest contributor to the fine PM fraction ($PM_{2.5}$) concentrations, both in concentration and percentage, especially at site 3. Combustion accounts for 35–92 percent of the total $PM_{2.5}$ concentration at the three sites (see figure 3-12). The ***suspended soil particles*** dominate the coarse fraction ($PM_{10\text{-}2.5}$), accounting for 70–90 percent of the total. This source also contributes to $PM_{2.5}$, particularly at the NRC site 2. When these two fractions are combined into PM_{10}, both soil and combustion contribute significantly to PM_{10}, but there is variation among the sites. Soil dominates at site 2 (NRC), combustion dominates at site 6 (III Khoroolol), while they contribute equally at site 3 (Zuun ail). ***The motor vehicles/road dust source*** accounts for about 3-12 percent of $PM_{2.5}$ at the three sites, and 5–20 percent of the coarse PM fraction, due to suspended road dust. ***The biomass contribution*** is very small except for PM_{10} at site 6, which is located in a ger area.

Figure 3-12: Concentration contributions (μg/m³) to PM in air from main sources in UB
Top: $PM_{2.5}$; Mid: $PM_{10\text{-}2.5}$; Bottom: PM_{10}



Source: Authors' illustration based on AMHIB monitoring.

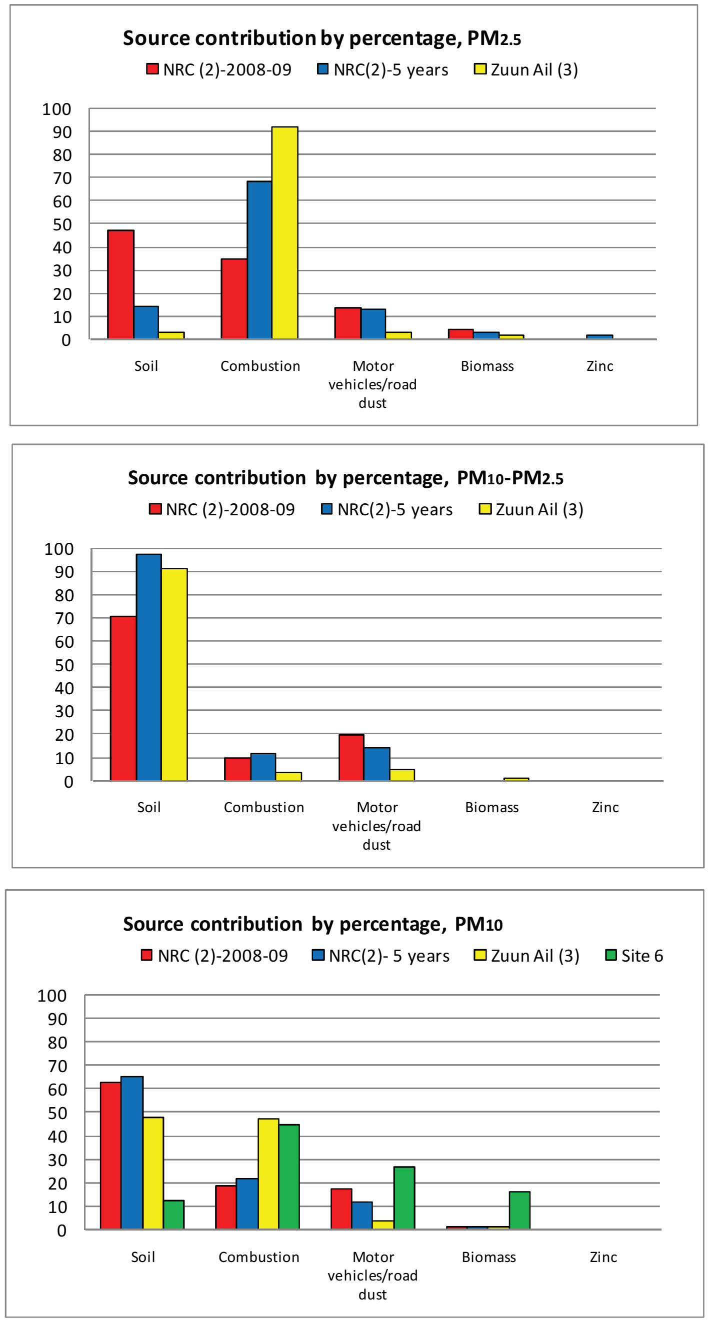
Discussion of source contributions

The source apportionment analysis indicates that coal combustion and soil suspension dominate as sources of PM at stations 2, 3, and 6, and that motor vehicles and biomass burning account for smaller contributions. There are significant differences between the stations in the amount of contributions to the different PM size fractions.

$PM_{2.5}$ (fine particle fraction) Soil suspension and coal combustion both make substantial contributions to $PM_{2.5}$ at site 2 (NRC), while coal combustion dominates completely at site 3 (Zuun Ail). This can be explained by the differences in site locations. NRC is located away from main ger areas but within an area with open and often dry soil surfaces, while Zuun Ail is exposed to ger area emissions with no extensive dry soil surfaces close to the station. Both are located well away from paved main roads and while there is traffic on smaller unpaved roads near the sites the motor vehicle contribution to $PM_{2.5}$ is low at both sites.

At NRC, there is some discrepancy between the AMHIB period and the three and a half-year period of analysis (2006-09). There was relatively more soil in the AMHIB period at the expense of

Figure 3-13: Relative contributions (percent) to PM in air from main sources in UB
Top: $PM_{2.5}$; Mid: $PM_{10-2.5}$; Bottom: PM_{10}.



Source: Authors' illustration based on AMHIB monitoring.

the coal combustion source, while the opposite holds for the three and a half-year period. Figure 3-9 shows that the $PM_{2.5}$ fraction was very high in the AMHIB period compared to earlier winters. The source apportionment analysis indicates that this increase is linked to a larger contribution from the soil source. It is possible that drier conditions in the AMHIB period led to increased fine particle suspension.

***$PM_{10\text{-}2.5}$* (coarse particle fraction)** Soil suspension dominates at both sites 2 and 3. The motor vehicle source provides a measurable contribution to both sites, due to road dust suspension. Although the distance to main roads is considerable, there is traffic on smaller unpaved roads near the sites. also In addition, traffic in the entire area causes road dust concentrations in the whole UB air shed.

PM_{10} PM_{10} is the sum of $PM_{2.5}$ and $PM_{10\text{-}2.5.}$ The $PM_{10\text{-}2.5}$ (coarse fraction) concentration is generally substantially higher than the $PM_{2.5}$ concentration (see figure 3-9). As a consequence of this and the above, soil dust suspension accounts for the largest contribution of PM_{10} at sites 2 and 3. Coal combustion is a very large source a site 3, while road dust makes a significant contribution to site 2.

For site 6, only PM_{10} apportionment has been carried out. Site 6 is located well within a ger area with small unpaved roads surrounding it. Hence coal combustion dominates this area and road dust gives a significant contribution, while also biomass (wood) burning and soil suspension are also noticeable as sources.

Combustion 1 (high-temp) vs. combustion 2 (low-temp) These two combustion-related profiles could be distinguished in the analysis of the fine PM fraction ($PM_{2.5}$) both at sites 2 (NRC) and 3 (Zuun ail). At site 2 (NRC), the two sources contribute about equally, corresponding to the location of site 2, which is away from main ger areas, but in an region with heat-only boilers. Also, the power plant emissions might contribute to this site, as it is located downwind of the power plant stacks at a distance where the power plant plumes could reach the ground. At site 3, which is exposed to ger area emissions, the source of combustion in Ger stoves dominates completely. At site 6, located within a Ger area where the combustion factor dominates completely, the analysis could not distinguish the two profiles.

Soil 1 vs. Soil 2 The two soil profiles could be separated in the analysis only for the coarse fraction at site 2 (NRC) where they contribute roughly equally to coarse PM at the sites. Thus, the general (Soil 1) and the more local (Soil 2) dust suspension sources appear to be equally important. This indicates that control of local soil suspension, e.g. by covering open surfaces, will only address part of the soil suspension problem.

Assessment of air pollution exposure through air pollution modeling

The spatial distribution of PM concentrations in UB and the contribution from main sources

Air pollution dispersion models applied and compared with measurements A state-of-the-art Eulerian grid model established for urban scale applications (Slørdal et al. 2003) was used to model the spatial and temporal air pollution concentrations in Ulaanbaatar for the AMHIB study. A diagnostic wind field model was used to provide the hourly meteorological data fields needed as input to the dispersion model. The emission inventory for Ulaanbaatar was used as input to an emissions model that provides hourly gridded emissions as input to the dispersion calculations. The models are described in annex C. The model calculations for Ulaanbaatar have concentrated on particulate matter, PM.

The software system platform AirQUIS was used to perform the modeling work for UB. The GIS-based AirQUIS system (AirQUIS 2008) is an integrated air quality management system that contains different modules for treating and combining various data such as emissions inventory data, geographical information data, measurement data, as well as the various models needed to perform dispersion and exposure calculations.

The dispersion model was evaluated by comparing the results from the modeling with those from the measurements and source apportionment analysis, as described in the previous two sections. Details of the evaluation are in annex C.

The comparison with concentration measurements shows that the modeled and measured annual $PM_{2.5}$ concentrations at stations 3, 4, 7, and 8 (located in ger areas) agree within 10 percent. The modeled concentration is also within the uncertainty range of the PM_{10} measured at station 3. This is also the case for PM_{10} at station 6, although the measured concentration is quite uncertain. Station 2, NRC, is located a couple of kilometers east of the UB central area. The model substantially overestimates the concentrations at this location, for PM_{10} and more so for $PM_{2.5}$. The model grids surrounding station 2 are, according to the population distribution, located within the ger areas with a high emission density. The emissions might also be overestimated for this area. Another explanatory factor could be that the model underestimates the windier conditions along the river valley area, where station 2 is located. More detailed wind measurements are needed to examine this issue further.

A comparison with the statistical source apportionment (SA) indicates that on the average for the three PM_{10} cases, the dispersion model gives about 10 percent (absolute) higher combustion contribution and about 14 percent lower soil and road dust contribution than the measured SA. The opposite applies for the two $PM_{2.5}$ cases, where the dispersion model gives approximately 17 percent lower combustion contribution and about 9 percent higher soil and road dust contribution than the measured SA.

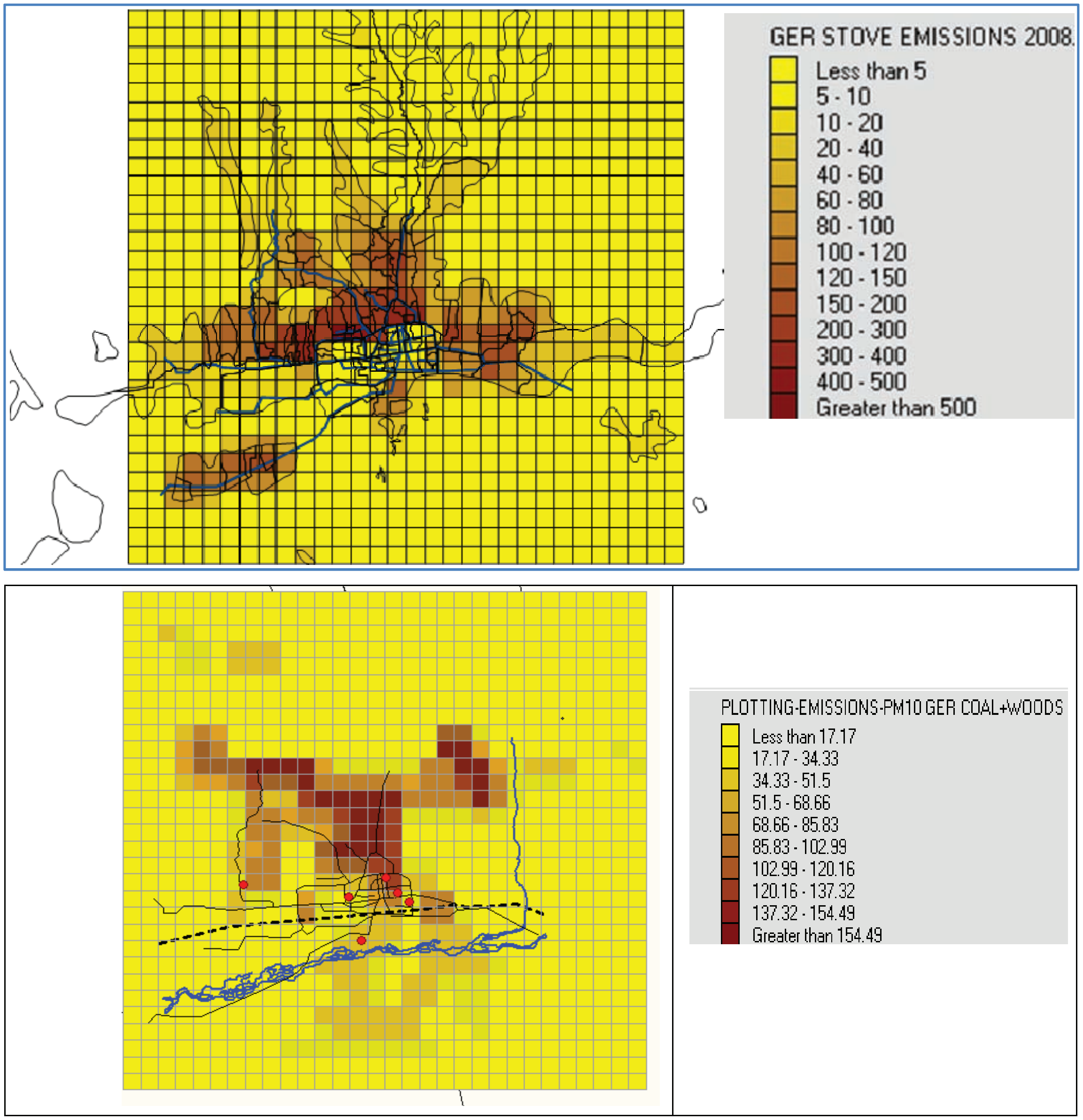
Therefore, it can be concluded that the dispersion model compares with the measurements of PM and its elemental composition sufficiently well to be used as a basis for cost effectiveness and cost-benefit analysis of abatement measures.

Main results from the update of the emissions inventory The emissions inventory resulting from the updated AMHIB study, as shown in table 4-3, is described in detail in annex C. Updated population data resulted in an increase in the calculated PM emissions from the ger households by 20.5 percent. The total emissions from the power plants (CHPs) and the heat-only boilers (HOBs) have also been modified, based upon new data and information. The road traffic (vehicle exhaust and road dust suspension) emissions are unchanged from the discussion paper (World Bank 2009). The even more significant change resulting from the updated population data is in the spatial distribution of the ger household emissions. The new population data resulted in a distribution much more concentrated in the ger areas closer to the UB central areas , a result that is important for the calculation of the spatial ground-level PM_{10} concentration distribution. Figure 3-14 shows the large change in ger area emissions distribution as a result of the new population distribution. In addition, the spatial distribution of HOB emissions changed to some degree.

Modeled present PM concentrations in UB, its spatial distribution and contributions from pollution sources Figure 3-15 shows the modeled spatial distribution of concentrations of PM_{10} and $PM_{2.5}$, as an annual average. The model calculates the average concentration in each of the km^2 grids. The concentrations vary considerably between different areas within UB, with the highest concentrations in the ger areas just north of the city's center. There is a very steep gradient toward lower concentrations when moving away from the ger area and south into the city. The PM_{10} concentrations reach as high as 900 $\mu g/m^3$, and the $PM_{2.5}$ as high as 550–600 $\mu g/m^3$, as an annual average. These are extremely high concentrations by any standard, including compared to Mongolia's own Air Quality Standards, which are 50 $\mu g/m^3$ for PM_{10} and 25 $\mu g/m^3$ for $PM_{2.5}$ (see earlier part of this chapter).

The calculated spatial distribution maps are in accordance with the general assessment of the

Figure 3-14: Spatial distribution of emissions from ger stoves, tons/km²/year

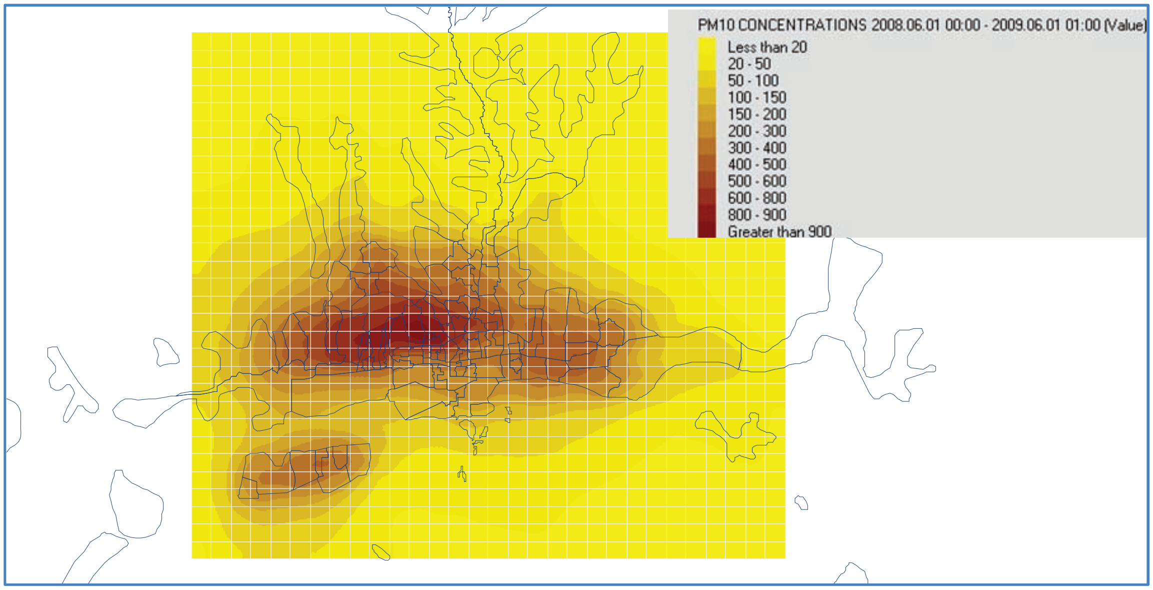


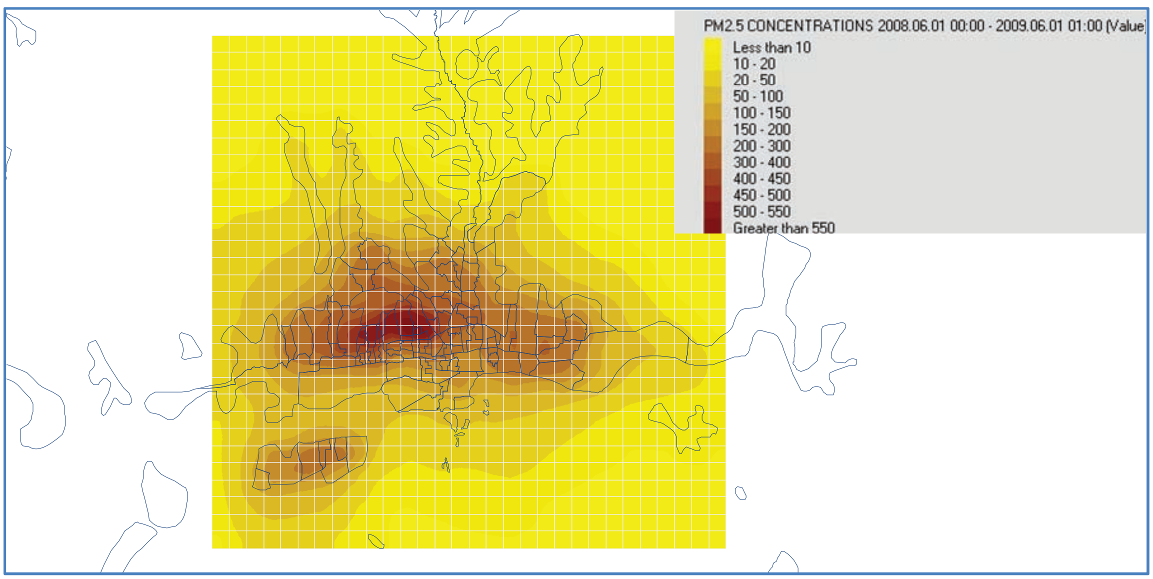
Note: The updated distribution (top) compared to the preliminary distribution used previously (bottom).
Source: World Bank 2009.

ranges of PM concentrations indicated from the results of the measurements and as summarized in table 3-1. From the evaluation of the model (see the section above and annex C), the results from the air pollution modeling provide an acceptable basis for assessing the PM concentrations and its distribution, contributions from sources, and subsequent assessments of the effects of various control scenarios on reducing PM pollution in Ulaanbaatar.

The contributions from the various categories of sources to the concentrations has been assessed both by measurements, and by the dispersion model calculations. Both methods indicate that combustion in ger heating systems and suspension of dry dust from open soil surfaces and roads are the main contributors to PM in UB. These two sources represent 75–95 percent of the PM concentrations, varying between locations, on the

Figure 3-15: Spatial distribution of PM_{10} (top) and $PM_{2.5}$ (bottom), annual average (µg/m³)





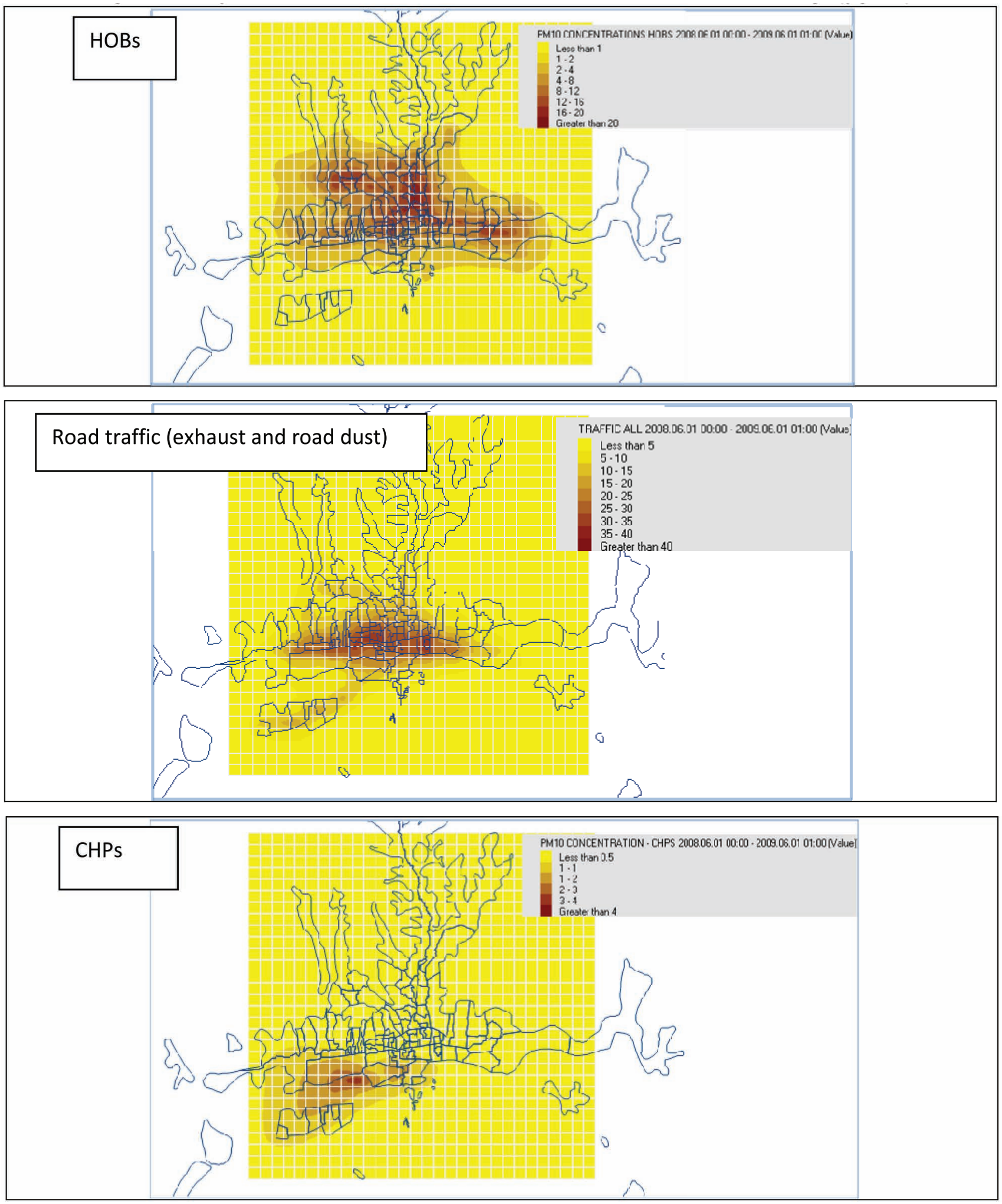
Note: Model calculations for the period June 2008 to May 2009.
Source: Authors' illustration based on AMHIB data.

higher end for $PM_{2.5}$ and on the lower end for PM_{10}. Vehicle exhaust from traffic accounts for only a minor contribution, except areas near the most heavily trafficked roads.

Maps of the spatial distribution of the contributions from the gers and from the soil suspension would be very similar to the total distribution shown in figure 3-15. Figures 3-16 and 3-17 show the spatial contributions from three of the less dominant source categories: HOBs, road traffic (including exhaust particles plus suspended road dust), and the power plants (CHPs), for PM_{10} and $PM_{2.5}$. The HOB distribution reflects the HOB locations and gives an estimated annual average PM concentration up to 20 µg/m³ for PM_{10} and 12 µg/m³ for $PM_{2.5}$ in the most affected areas. The traffic

contribution is concentrated in the city center and its contribution is quite substantial in this area, with an estimated annual average up to and above 40 μg/m³ for PM_{10} and 24 μg/m³ for $PM_{2.5}$ in the most affected areas. The influence of traffic contribution is considerably lower in the ger areas in general, although it is substantial near main roads, especially because of road dust suspension. The CHP distribution is mostly downwind of the power plants in the direction of the prevailing

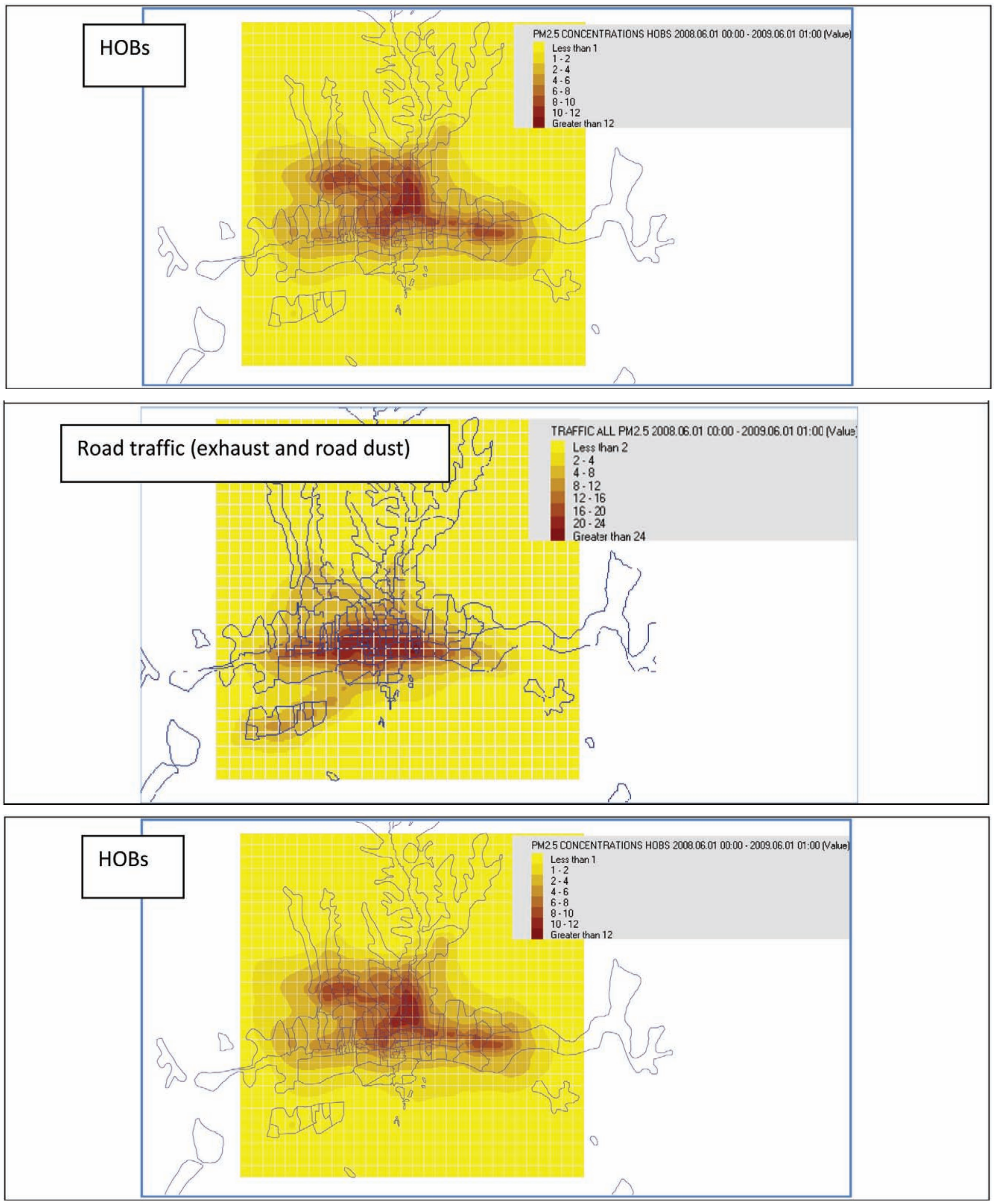
Figure 3-16: Spatial distribution of source contributions, PM_{10}, annual average (μg/m³)



Note: Model calculations for the period June 2008 to May 2009.
Source: Authors' illustration based on AMHIB data.

westerly wind. Its calculated contribution to annual average PM concentrations is comparatively low. CHP emissions and resulting ground-level concentrations can rise in shorter periods (less than several hours) when suitable meteorological conditions allow the plumes from the chimneys to reach the ground level, particularly if this weather coincides with periods when the cleaning equipment of the power plants cleaning equipment is not operating properly.

Figure 3-17: Spatial distribution of source contributions, $PM_{2.5}$, annual average ($\mu g/m^3$)



Note: Model calculations for the period June 2008 to May 2009.
Source: Authors' illustration based on AMHIB data.

The exposure of the UB population to PM concentrations, and its source contributions

The exposure of the population of Ulaanbaatar to PM in the air is calculated in terms of the population-weighted averaged concentration, the PWE, as described in chapter 2. Table 3-4 gives the calculated PWE for PM_{10} and $PM_{2.5}$ for UB for the AMHIB period June 2008–May 2009 and present the contributions to PWE, calculated from the various main sources.

Emissions from the ger heating systems (burning coal and wood in stoves and small boilers in ger housing units and kiosks in the ger areas) account for the largest contribution to the PWE (46 percent for PM_{10} and 60 percent for $PM_{2.5)}$. Wind-blown dust from open surfaces in the city represents the second largest source of PWE (31 percent for PM_{10} and 16 percent for $PM_{2.5}$). Combustion residues, essentially ash and soot accumulating in ger stoves, which are dumped in open space and dispersed by the wind, contribute 11 percent and 15 percent to PM_{10} and $PM_{2.5}$ concentrations, respectively. Power plants, although representing a large emission source, provide only a relatively small contribution because their tall chimneys lift the power plant plumes and do not, according to the model calculations, influence ground level in the more populated areas most of the time. Vehicle exhaust also makes only a small contribution, since total PM emissions from road traffic is relatively small, although the suspension of road dust makes a noticeable contribution to the levels of PM_{10}.

Table 3-4: Population-weighted exposure (PWE) to PM in Ulaanbaatar as calculated by the air pollution model, contributions from main sources (µg/m³)

	PM_{10}	$PM_{2.5}$
Gers stoves	195.6	156.5
HOBs	9.0	5.4
CHPs	0.3	0.1
Exhaust particles	9.2	9.2
Road dust	29.9	9.0
Windblown dust	134.4	40.3
Combustion residues	48.9	39.1
Total	**427.3**	**259.6**

Source: AMHIB data.

Implications of air pollution mapping for the monitoring network in UB

The mapping of the PM concentration distribution in Ulaanbaatar, both from the monitoring results and from the modeling, provided a basis for recommendations on improving the stationary air pollution monitoring network in UB. For example, the mapping shows that parts of the ger areas have much higher concentrations than the central districts. This leads to the conclusion that the stationary air pollution monitoring network in UB should include automatic stations in the ger districts. In chapter A8 in annex A, recommendations regarding the design and content of a stationary long-term monitoring network in UB have been developed. The recommendations were based on an overview of the existing AMHIB and the availability of modern monitoring equipment, both within the Mongolian and UB institutions as well as through the German and French donor programs. (see annex A) One of the main recommendations is to also establish modern monitoring stations in the ger districts. A suggested monitoring network is included in figure A.34.

The suggested minimum network includes:

- 3 urban background stations in the most polluted ger areas
- 1 to 3 urban background stations in central areas
- 1 station between ger and central areas
- 3 traffic stations (located near main road links)
- 1 reference station in a relatively clean area
- some additional specialized sites.

The final design of a long-term monitoring network should result from discussions among the stakeholders.

4. Estimating the Effects of Air Pollution on Mortality and Hospitalization in Ulaanbaatar

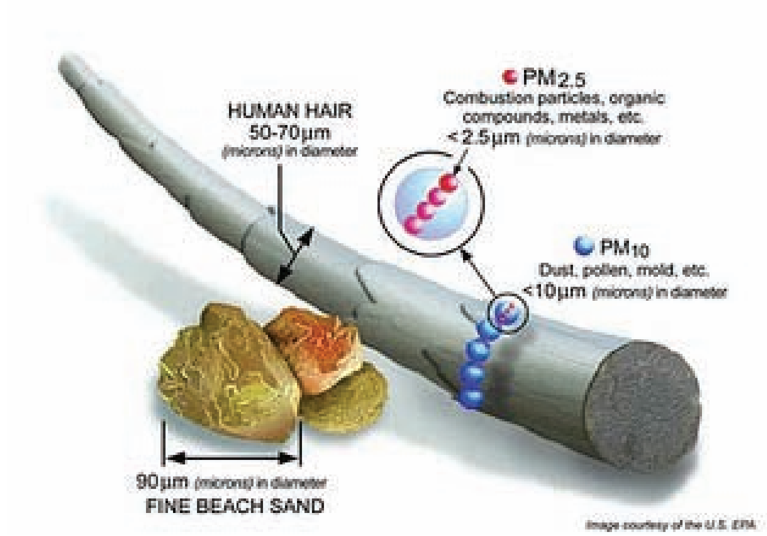
This chapter summarizes the statistical analysis of the association between daily exposure to air pollution and both premature death (mortality) and hospitalization (morbidity) using one year of data from Ulaanbaatar. The analysis involved consideration of daily concentrations of four pollutants: PM_{10} and $PM_{2.5}$ (particulate matter less than 10 microns and 2.5 microns in diameter, respectively), coarse particles (particles between 2.5 and 10 microns), and nitrogen dioxide. While analysis of this nature generally requires several years of data to ensure that the data are sufficiently detailed to detect an effect, several important results were obtained. The study team observed that when using the full year of data collected, daily exposure to coarse particles was associated with increases in mortality. In addition, a strong effect was observed between $PM_{2.5}$ and mortality during the warm season, when people have greater exposure to outdoor air. Strong associations were observed for hospital admissions for both heart and lung disease with $PM_{2.5}$, PM_{10}, and nitrogen dioxide. The effect estimates for mortality and morbidity, measured as the percent change in the health outcome per every unit change in the pollutant concentration, were generally similar in magnitude to those reported in studies in North America, Europe, and other parts of Asia. Thus, despite the relative sparseness of data, the findings indicate that particulate matter and other pollutants in UB have serious negative effects on public health. Additional years of data would help confirm these findings and also aid in determining the sources of pollution that have most significant impact on health.

Introduction

This chapter summarizes the results of an analysis of the association between air pollution and both premature death and hospitalization in UB. The study team compared data on daily readings from particulate matter (PM) monitors with concurrent data from health records from UB. Specifically, the team examined whether concentrations of $PM_{2.5}$, PM_{10}, and coarse particles (CP) are statistically related to either premature death (mortality) or additional hospital admissions (morbidity) from either heart or lung disease. Fine particles more easily evade the natural defense mechanisms in the human airways than coarse particles and are more likely to penetrate deeply into the lungs. The coarse particles will more likely be filtered out by the nose and upper airways. However, if the concentration of coarse particles (and hence PM_{10}) is particularly high, there is evidence that they also will cause significant health effects (Malig and Ostro 2009). Figure 4-1 indicates the relative size of particles.

The ambient concentrations of both $PM_{2.5}$ and PM_{10} in UB are extremely high. Therefore, it is important to determine the magnitude of their effects on public health. Besides PM, the impacts of nitrogen dioxide (NO_2)—a product of fuel combustion—are also examined in this analysis. As is the case for PM, associations between NO_2 and both death and disease have been observed in epidemiologic studies (U.S. EPA 2008). Accordingly, the study team analyzed the relationship between daily exposures to PM and NO_2 with both mortality and hospital admissions in UB.

Figure 4-1: The size of $PM_{2.5}$ and PM_{10} relative to human hair and beach sand



Source: Courtesy of U.S. EPA.

For this epidemiological analysis, the study team used methods similar to those used over the last decade to examine the relationship between daily exposure to air pollution and subsequent health effects. These studies, conducted in dozens of cities around the world, have demonstrated statistical associations between several adverse health outcomes and daily, multiday, and long-term (one year to several years) changes in outdoor air pollutants, including particulate matter (PM) (Brook et al. 2010). As summarized in Figure 4-2, there is a wide range in the severity of health outcomes associated with PM, including minor respiratory symptoms, asthma attacks, emergency room visits, heart attacks, hospital admissions, and death.

In the following sections, the methodology used and the subsequent analytic results of effects due to daily changes in PM_{10}, $PM_{2.5}$, CP, and NO_2 are presented using the one year of currently available data in UB. The estimated effects of exposure to these pollutants on specific diseases resulting in either death or hospital admissions have been summarized. Most studies of this kind use several years of data, and therefore the results presented below, particularly for mortality, should be viewed as preliminary, pending additional years of analysis. Details on the complete analysis and a discussion of the results are in annex D.

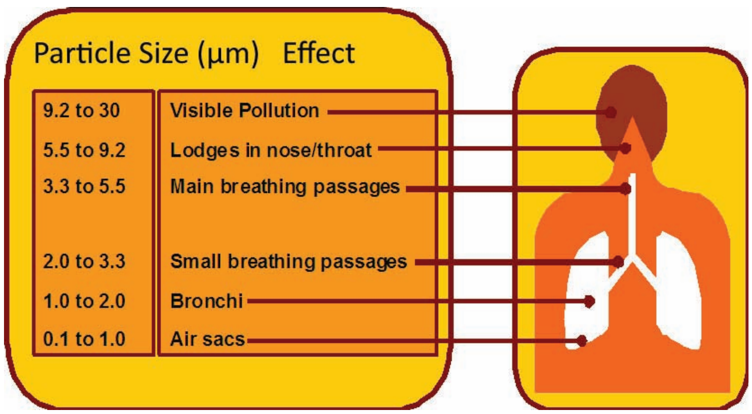
Data and Methods

Exposure data

All pollution data were obtained from the Air Monitoring and Health Impacts Baseline (AMHIB) study, sponsored by the World Bank and based on recommendations from several Mongolian representatives. Data cover the period from June 2008 to May 2009. The PM_{10} and $PM_{2.5}$ data come from a network of eight monitoring stations (see figure 3-1 and table 4-1). Figure 4-3 shows the administrative districts in UB and the approximate location of the monitoring stations relative to the district borders. Pollution data included 24-hour averages of PM_{10}, $PM_{2.5}$, CP, and NO_2. CP was calculated by subtracting $PM_{2.5}$ from PM_{10}. Data were sampled twice a week, on Wednesdays and Sundays. In addition, there were six weeks, mostly during the winter, when data were collected every

Figure 4-2: Health effects of particulate matter

Increased respiratory symptoms
Decreased lung function
School and work loss
Aggravated asthma
Adverse birth outcomes
Development of chronic bronchitis
Irregular heartbeat
Emergency room visits
Nonfatal heart attacks
Hospital admissions
Premature death in people with heart or lung disease



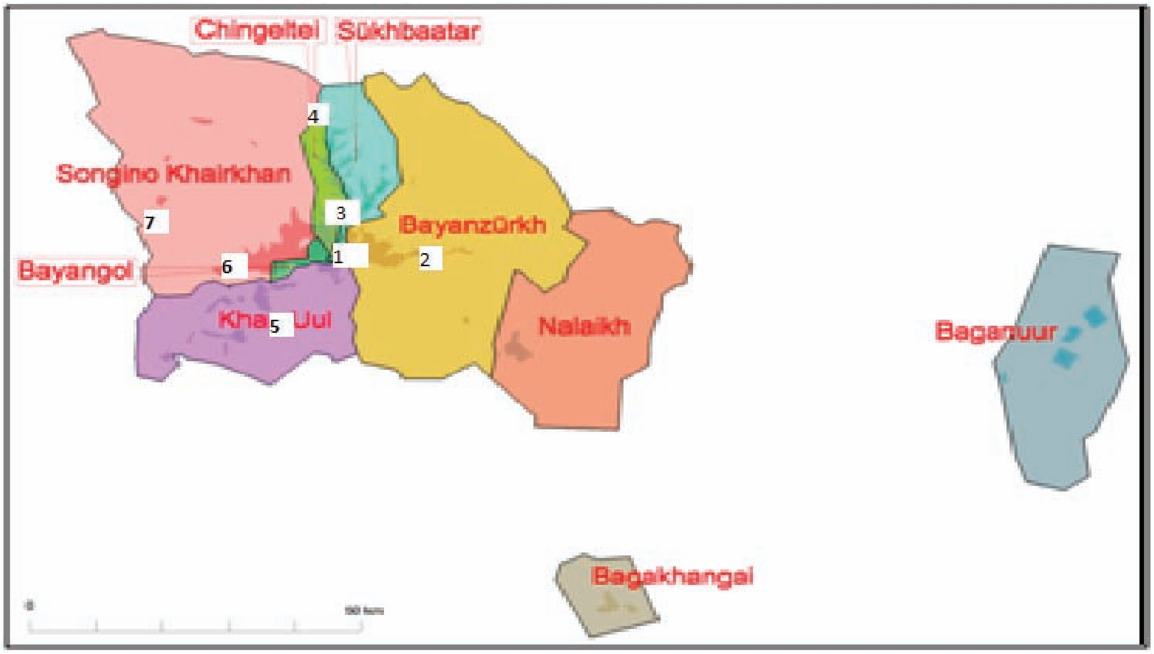
Source: Guttikunda (2007) and authors' illustration based on AMHIB monitoring.

day. Unfortunately, wide variations in sampling methods were used for $PM_{2.5}$ and PM_{10} and comparisons among instruments show significant discrepancies (see annex C). In addition, humidity has a differential impact on the accuracy of the measurements of the different monitors. These errors in measuring actual pollution levels may reduce the likelihood of observing a health effect. The study team attempted to minimize this problem by selecting only a subset of the existing monitors. It is still likely that the health effects will be underestimated, although it is difficult to determine from the available data how much higher the ¨true¨ effect would be. Data for NO_2 were provided as an average of the four NO_2 monitors in UB.

Mortality and hospitalization data

These six districts had a total population of approximately 930,000 in 2008. The other three districts were very small (total population under 60,000), were spatially distinct from the rest of the urban area of UB, and the population exposures are not well represented by the monitors. Therefore, the analysis was restricted to the more populated and contiguous six districts. For mortality, both "natural" and cardiovascular deaths were examined. Natural mortality is defined as total mortality minus deaths due to injuries, accidents, violence, and suicides (and labeled, in this analysis, as "all-cause mortality") since these latter causes are not likely to be

Figure 4-3: Administrative Zones and AMHIB Stations, Ulaanbaatar, Mongolia



Source: Authors' illustration based on AMHIB monitoring.

Table 4-1: PM monitor stations and associated hospital districts

Station #	Station Name	Sampler Method	PM Size Fraction	Monitor Operating Period
1	NAMHEM	Kosa Monitor	PM_{10}, $PM_{2.5}$	6/08–5/29
2	NRC	GENT Sampler	PM_{10}, $PM_{2.5}$	6/08–5/29
3	Zun ail	GENT Sampler	PM_{10}, $PM_{2.5}$	6/08–5/29
4	Buudal	Dust-Trak 8520	$PM_{2.5}$	6/08, 9/08–5/
5	CLEM	Rotary Bebicon	PM_{10}	6/08–5/29
6	III khoroolol	Partisol FRM-Model 2000	PM_{10}	6/08–5/29
7	SKHD_7 (Bayankhoshuu)	Dust-Trak 8520	$PM_{2.5}$	6/08–5/29
8	NISEH_8 (Airport)	Dust-Trak 8520	$PM_{2.5}$	6/08, 9/08–5/09

Source: AMHIB study.

Table 4-2: Administrative district with associated PM monitor and population

District*	Name	$PM_{2.5}$ Monitor Used	PM_{10} Monitor Used	2008 Pop
1	Bayangol	1	6	160,818
2	Bayanzurkh	2	2	211,614
3	Songinokhairkhan	7	6	211,056
4	Sukhbaatar	3	3	123,041
5	Khan Uul	1	5	90,925
6	Chingeltei	4	3	132,883

Note: Districts 7, 8 and 9 did not have a nearby PM monitor and were excluded from the analysis.
Source of Population data: World Bank. 2009. *Air Pollution in Ulaanbaatar: Initial Assessment of Current Situation and Effects of Abatement Measures.* Washington, DC: World Bank.

related to pollution exposure. For hospitalization, both cardiovascular and respiratory admissions were examined. The coding of cause of death and hospitalization was based on the current international standard—the tenth version of the International Classification of Diseases, (ICD-10), codes S through Z. In addition, for both mortality and morbidity, cases due specifically to either cardiovascular or respiratory disease were examined. Cardiovascular deaths and hospitalizations were assigned ICD codes starting with "I," while ICD codes for respiratory cases began with "J."

Assigning Exposure

In such a study it is crucial to utilize the pollutant measurements that most accurately reflect the actual exposures. Statistical studies have shown that errors in the measurement of exposure are likely to underestimate the true effect of pollution and make it more difficult to find a "statistically significant" effect of pollution. Conceptually, statistical significance is an estimated pollution effect that is not due to chance alone and one that would be observed repeatedly in replicated studies. In order to estimate the exposure of the population to ambient concentrations of studied pollutants, the population distribution needs to be superimposed on the distribution of these ambient concentrations. The level of accuracy depends on resources and data availability.

To assign exposure for the particle metrics, the administrative district of residence (and presumed location of the deaths and hospitalizations) was matched with the closest PM monitor (see figure 4-3). This was undertaken in order to minimize the misclassification of pollution exposure, given the distinct spatial orientation of the city and surrounding ger areas. Table 4-2 summarizes the matches between event location and monitor. Of the eight monitors that were initially available for the analysis, only monitor #8 (Airport) and #5 (CLEM) were not used. The former was not used since it is located at the airport, a significant distance away from the center city, and the latter was not used since it only measured PM_{10} and these measurements had unexplainable variations—they were much lower than all other monitors, and even lower than the $PM_{2.5}$ measurements for the same district (from a different monitor). It is important to note that the monitor corresponding to Administration District 1 (AMHIB station 6, III khoroolol) only measures PM_{10}. However, AMHIB station #1 also matches up with Administrative District 1, so District 1 residents were assigned $PM_{2.5}$ data from that monitor. Likewise, station #6 only measures PM_{10} for District 3, so $PM_{2.5}$ data were taken

from nearby station #7. Similar substitutions were made in other districts using nearby monitors. The study team also explored other options for assigning exposure, but the subsequent results were not quantitatively different from those using this method.

Method

As in many previous studies (Malig and Ostro 2008), a time-stratified case-crossover study design was used. This design is similar to the case-control study often used in epidemiology. In the case-crossover method, pollution on the date of the death (case) is compared to pollution on several other referent days (controls) occurring within the same month and year. As a result, each individual in the study serves as his or her own control and there is matching on a wide range of individual-level characteristics. This method significantly reduces the likelihood that some unmeasured factors will affect the results. As a result, most factors that can have an impact on mortality and that vary on a daily basis with pollution are implicitly taken into account by the study design. In addition, by limiting cases and controls to the same month, factors that vary over a longer time scale (e.g., smoking, diet, exercise, age) will not change. Thus, these factors will not have an impact on the statistical analysis. The basic analysis involves the full year of data collected in UB. However, given the large differences in concentrations and sources of PM by season, a sensitivity analysis for mortality was conducted by dividing the year into a cold and warm season. The latter was defined as May through September.

Logistic regression analysis was used to estimate the impact of pollution exposure on health (morbidity and mortality) and the accuracy (predictive value) of the model's estimate. The goal of the logistic regression is to determine the best fitting model to describe the relationship, in this case, between death on a given day (the dependent variable) and pollution (the predictor). A logistic regression will generate a coefficient (an effect per unit of the pollutant) and significance level (an indication of the likelihood of the observed effect). In this model, the probability of the occurrence of death (or hospitalization) is examined to determine whether it is more likely to occur on days of higher air pollution.

In the analysis, both the same day of exposure (i.e., without a lag in the response time or lag0) and previous days of exposure are tested to see if they have an impact on mortality. This is important since it is likely that an adverse health effect will occur several days after the actual exposure occurs. Thus, besides lag0, the study team examined exposures up to three days before the event (e.g., lag1, lag2 and lag3). Results are presented in terms of the percent increase in the health effect over the existing conditions, per every 10 micrograms per cubic meter ($\mu g/m^3$) increase in the air pollutant being measured. The latter is a standard measure of the amount of particles found in the air. Besides this central estimate, a 95 percent confidence interval is also provided. This provides a range within which the true value is likely to fall 95 percent of the time if other studies were conducted with similar data.

Results

The distributions (i.e., mean and median) of the pollution data used in the analysis of premature mortality are summarized in table 4-3. For example, for the mortality analysis, based on all of the districts, the average temperature was –2 C°, and the mean pollution concentrations of NO_2, PM_{10}, $PM_{2.5}$ and CP (in $\mu g/m^3$) were 29, 486, 301 and 206, respectively. Median PM_{10}, $PM_{2.5}$ and CP are much lower at 227, 95, and 112 $\mu g/m^3$, respectively, due to the skewed distribution and the very high concentrations that occur in the winter. As expected, PM concentrations vary widely among districts. For example, median $PM_{2.5}$ ranges from 42 $\mu g/m^3$ in District 6 to 256 $\mu g/m^3$ in District 3.

Table 4-4 summarizes the pollution data used in the analysis of hospital admissions and table 4-5 summarizes the mortality and hospital data. The mean age at death was 56.3, with 1,425 cases of all-cause mortality, 568 cardiovascular (40 percent of the total), and 53 respiratory (4 percent of the total). Males made up about 57 percent of all mortality. Due to the small

Table 4-3: Descriptive statistics of data used in mortality analysis

District (number of cases)	Statistic	Temperature (C °)	NO_2 (µg/m³)	PM10 (µg/m³)	PM2.5 (µg/m³)	CP (µg/m³)
All (n = 1,425)	Median	-2	28	227	95	112
	Mean	-2	29	486	301	206
All (warm season) (n = 462)	Median	15	25	125	26	104
	Mean	15	27	200	65	152
All (cool season) (n = 963)	Median	-10	29	276	141	122
	Mean	-10	30	609	388	225
1 (n = 200)	Median	-2	28	220	38	159
	Mean	-1	29	401	68	343
2 (n = 346)	Median	-2	28	184	63	105
	Mean	-1	29	264	136	153
3 (n = 304)	Median	-5	28	229	244	0
	Mean	-3	28	432	713	-217
4 (n = 178)	Median	-2	28	275	144	171
	Mean	-3	29	785	409	386
5 (n = 161)	Median	-2	28	214	39	155
	Mean	-1	29	401	69	343
6 (n = 236)	Median	-5	28	275	198	74
	Mean	-3	29	778	403	402

Source: AMHIB data.

Table 4-4: Descriptive statistics of data used in hospital analysis

District (number of cases)	Statistic	Temperature (C °)	NO_2 (µg/m³)	PM10 (µg/m³)	PM2.5 (µg/m³)	CP (µg/m³)
All (n = 28,282)	Median	-8	28	273	85	189
	Mean	-6	28	534	233	330
1 (n = 11,664)	Median	-6	28	287	42	230
	Mean	-6	27	465	74	396
2 (n = 6,079)	Median	-11	30	215	95	105
	Mean	-9	30	285	177	151
3 (n = 2,336)	Median	8	28	129	248	6
	Mean	5	28	301	754	-225
4 (n=6,015)	Median	-9	28	393	198	213
	Mean	-7	28	895	493	405
5 (n = 1,235)	Median	-5	28	287	39	244
	Mean	-2	29	473	67	405
6 (n = 843)	Median	-12	28	671	198	344
	Mean	-7	28	1262	441	806

Source: AMHIB data.

Table 4-5: Descriptive statistics for mortality and hospitalization data used in analysis

	All-cause	Cardio	Resp	Other	Female	Male	Mean Age
Mortality	1,425	568	53	804	613	812	56.3
Hospitalization		6,291	21,991	-	15,637	12,645	41.0

Source: AMHIB data.

Table 4-6: Statistically significant or near significant mortality effect estimates for particulate matter and nit-ogen dioxide, June 2008–May 2009

Season	Outcome	Variable	Lag	Percent change per each 10 μg/m³ in PM or 1 μg/m³ NO_2	95% confidence interval
Full year	Cardiovascular	CP	1	0.25	0, 0.51
Full year	Cardiovascular	CP	3	0.25	-0.05, 0.55
Full year	All-cause	NO_2	1	0.84	-0.10, 1.78
Full year	Cardiovascular	NO_2	1	1.23	-0.25, 2.71
Warm	All-cause	PM2.5	2	1.38	0.42, 2.44
Warm	All-cause	PM10	2	0.53	-0.04, 1.15
Cold	Cardiovascular	CP	1	0.27	0.01, 0.54
Cold	Cardiovascular	CP	3	0.28	-0.04, 0.50

Source: AMHIB data.

amount of respiratory-specific mortality, it was dropped from subsequent analysis. Regarding hospitalizations, there were 6,291 cardiovascular-specific and 21,991 respiratory-specific admissions. Males made up 44.7 percent of the cardiovascular and respiratory hospital admissions.

Table 4-6 summarizes the statistically significant regression results (i.e., associations between pollution and health that are unlikely to be due to chance alone) for the pollution data collected between June 2008 and May 2009 (for the full set of results, see annex D). Using the full year of data on particulate matter, the only associations observed were between cardiovascular mortality and coarse particles with a one-day lag. The results suggest that every 10 μg/m³ change in coarse particles would increase daily cardiovascular mortality on the next day by 0.25 percent (95 percent confidence interval = 0, 0.51). Additional associations were observed when the data were stratified by season. For example, in the warm season there were associations between $PM_{2.5}$ and all-cause mortality, with each 10 μg/m³ increase relating to a subsequent 1.4 percent increase in daily mortality. In the cold season, coarse particles were associated with cardiovascular mortality. In this case, a one-day lag in these particles was associated with a 0.28 percent increase in mortality on the following day. Full-year analysis of NO_2 showed modest associations with both all-cause and cardiovascular mortality based on the previous day's exposure (i.e., a one-day lag). Exposures to NO_2 were not stratified by season since the concentrations were reasonably similar in both the warm and cold season.

Table 4-7 summarizes selected results for hospital admissions for both cardiovascular and respiratory disease. Unlike the case for mortality, there were many strong associations between particulate matter and hospitalizations (the full set of results are presented in annex D). For many of the outcomes, the three-day lag between exposure and hospital admissions generated the best fit of the data and the largest impacts. For example, for each 10 μg/m³ change in $PM_{2.5}$, a 3-day lag was associated with a 0.82 percent increase in admissions for cardiovascular disease and a 0.24 percent increase for respiratory

Table 4-7: Selected statistically significant results of logistic regressions for hospitalization and particulate matter, June 2008–May 2009

Outcome	Variable	Lag	Percent change per each 10 µg/m³ in PM or 1 µg/m³ NO2	95% confidence interval
Cardiovascular	$PM_{2.5}$	3	0.82	0.64, 1.00
Respiratory	$PM_{2.5}$	3	0.24	0.14, 0.34
Cardiovascular	PM_{10}	3	0.21	0.11, 0.31
Respiratory	PM_{10}	2	0.04	0, 0.08
Respiratory	CP	0	0.05	0.01, 0.09
Cardiovascular	NO_2	3	1.38	0.84, 1.12
Respiratory	NO_2	3	1.20	0.88, 1.52

Note: PM_{10}, $PM_{2.5}$, CP = particulate matter less than 10 microns, less than 2.5 microns, and between 2.5 and microns, respectively; Lag = number of days prior to death that the exposure occurs; confidence interval = likely range within which the true value is likely to fall 95 percent of the time if many other studies were conducted with similar data.
Source: AMHIB study.

disease. For a 10 µg/m³ change PM_{10}, a 3-day lag was associated with a 0.21 percent increase in cardiovascular admissions, while a 2-day lag was associated with a 0.04 percent increase in respiratory admissions. Coarse particles did not appear to have a significant effect on hospitalizations in this sample and only a small effect on respiratory admissions was observed. Effects were also observed between NO_2 and both cardiovascular and respiratory admissions, with a 3-day lag (i.e., exposure three days prior to the effect) being the most important.

Summary and Discussion

UB's population is exposed to high concentrations of PM from different sources, each with different chemical constituents and size fractions. The findings from the limited one year of available data support the conclusion that there are significant public health implications related to air pollution in UB. However, because most similar studies involve several years of data, it would be important to repeat this study once more data are available. Nevertheless, several important associations were observed between daily changes in PM and NO_2 and both mortality and morbidity. This is particularly noteworthy given the scarcity of data, i.e. only one year of data generally collected on an every third or sixth day basis. The sparseness of the data also could lead to inaccurate or unstable results.

For mortality, the strongest associations using the full year of particle data were observed for coarse particles. Specifically, coarse-particle concentrations were associated with cardiovascular mortality on the following day. Exposure to coarse particles was associated with an increase of approximately 0.3 percent per every 10 µg/m³ change. However, given the very high exposures to these pollutants in UB, exposures equal to the interquartile range (a metric commonly used in air pollution epidemiology studies signifying the amount between the 75th and 25th percentile of the distribution) would generate a daily increase in mortality of about seven percent above the normal levels. In addition, a strong effect was observed between $PM_{2.5}$ and mortality during the warm season. The magnitude of this effect is generally similar to, but at the higher end of, the range of effects observed in previous studies of $PM_{2.5}$ in other parts of the world. Based on the interquartile range observed during the warm season in UB, this would relate to about a four percent increase in daily mortality over baseline. Finally, more modest associations (i.e., somewhat less statistically significant) were observed in the analysis of the full-year of data on NO_2 with both all-cause and cardiovascular mortality.

For hospital admissions, the strongest associations were observed for $PM_{2.5}$ and PM_{10} with cardiovascular disease. Using the IQR, exposures to $PM_{2.5}$ and PM_{10} could increase daily hospital admissions for cardiovascular disease by approximately nine percent over the normal level of hospitalizations. Associations were also observed for NO_2, particularly with hospitalizations for cardiovascular disease.

There are several possible explanations for the lack of an effect of $PM_{2.5}$ in the full-year analysis, but an observed effect during the warm season. The first factor might be the differential seasonal pattern of sources and exposures during the year. It is possible that during the winter, exposure to $PM_{2.5}$ is easier to avert for the majority of the population living in houses and apartments in the central city. About half of the population of UB lives in apartments located in the central areas of the city. About 80 percent of these apartments are supplied with central heating and hot water from three power plants located to the west of the city. The remainder of the apartments is supplied by local boilers. It is likely that during the warmer months, when an effect of $PM_{2.5}$ on mortality was observed, residents will spend more time outdoors (or indoors with windows open) and incur greater exposures. Several previous studies have reported effects of $PM_{2.5}$ in particular seasons. For example, in a study of 100 U.S. cities from 1987 to 2000 (see references in World Bank 2009), found strong effects of $PM_{2.5}$ on mortality during the warmer months, particularly in the northern sections of the U.S. which experience significant seasonality in climate. Second, the toxicity of the components of $PM_{2.5}$ may be different in the summer than the winter. Third, the full-year mortality results may also be due to low statistical power (i.e., the ability to detect an effect) in the study. While strong and consistent associations were observed between $PM_{2.5}$ and hospital admissions for cardiovascular disease with many more cases, the low number of cases of daily mortality makes it much more difficult to statistically detect an effect. Therefore, given the strong and consistent effects observed for hospitalization and the likely similar biological mechanisms, an effect on mortality would be expected. Further, it is likely that with an additional year of data, the signal from $PM_{2.5}$ will become stronger and the public health burden will become more obvious.

In summary, the population of UB is exposed to high concentrations of PM from different sources and with different chemistry and size fractions. There is existing scientific literature to suggest that many of these sources—coal combustion, local boilers, motor vehicles, biomass, and even crustal material—can contribute to adverse health effects, especially at the concentrations experienced in UB. The findings of this analysis of the limited available data support the conclusion that there is a significant public health burden related to exposure to air pollution in UB.

Implications

The following is a simple example to illustrate the quantitative health implications of the above results for short-term changes in $PM_{2.5}$. For this exercise, a hypothetical change from the current annual concentration of 260 μg/m^3 to the current annual standard of 25 μg/m^3 is assumed. Recall that the analysis indicates that during the warm season, every 10 μg/m^3 change in $PM_{2.5}$ would result in a 1.38 percent (95 percent CI = 0.42, 2.44) increase in daily mortality and that over the full year, a similar change in $PM_{2.5}$ results in a 0.82 percent (95 percent CI = 0.64, 1.00) change in hospital admissions for cardiovascular disease and a 0.24 percent (95 percent CI = 0.14, 0.34) change in hospital admissions for respiratory disease. It is assumed that the estimated relationship between the percent change in health and $PM_{2.5}$ is linear (i.e. there is a constant slope or effect per μg/m^3 over the entire range). At very high concentrations, this relationship would have to become less than linear; that is, the slope would be lower. It is also assumed for simplicity that the annual change consists of 365 daily changes of a similar amount. This assumption does not alter the overall findings. There are approximately 11 deaths per day during the warm season and 55.5 and 190 cardiovascular and respiratory admissions per day throughout the year, respectively. These averages are based on the data and sample used in the analysis; that is, using the period from June

2008 to May 2009, for people living in one of the six administrative districts in the study, and using total mortality minus homicides, accidents, and injuries.

The annual impacts, therefore, for mortality (DM) can be calculated by:

$$DM = \text{change in } PM_{2.5} \times \text{\% change mortality per } \mu g/m^3 \times \text{baseline daily mortality rate} \times 146 \text{ days of the warm season}$$

$$= (260 - 25) \times 0.138\% \times 11 \times 146 = 521 \text{ deaths or } 11\% \text{ of all deaths}$$

Thus, given these model assumptions, meeting the standard would reduce premature mortality from short-term exposures by 521 deaths per year, with a 95 percent confidence interval of 160 to 920. This amounts to a 13 percent reduction in mortality with a 95 percent confidence interval of four percent to 22 percent. Using the same calculations for hospital admissions, the attainment of the $PM_{2.5}$ standard would reduce annual cardiovascular hospital admissions by 3,900 (95 percent CI = 3,050 − 4,760) and respiratory hospital admissions by 3,910 (95 percent CI = 2,280 − 5,540).

As indicated above, many of the ger areas were not included in this epidemiological study because the existing monitors were not necessarily representative of exposures in those areas and the population sample size was small. Chapter 3 indicates that the $PM_{2.5}$ concentrations in these areas are much higher than those reported the central city with an annual average $PM_{2.5}$ in the range of 200 to 350 $\mu g/m^3$. The source mix for the particles in the ger areas will be somewhat different from that in the central city since the sources are dominated by extensive coal burning for heat and power generation (particularly during the winter) and the blowing of dust. If it is assumed, however, that the toxicity of $PM_{2.5}$ in these areas is generally similar to that in the urban area, we can provide a general quantitative assessment of the likely health impact. It is also necessary to assume that the concentration-response function remains linear (i.e., the slope or effect per $\mu g/m^3$ is constant) at the higher levels of $PM_{2.5}$. If so, this suggests that the ger areas will have a 1.38 percent increase in daily mortality per every 10 $\mu g/m^3$ in $PM_{2.5}$. Using the average of the likely annual range of 275 $\mu g/m^3$ for $PM_{2.5}$ in the ger areas, a daily change from this concentration to the current annual standard of 25 $\mu g/m^3$ would suggest a 34 percent increase in mortality above the normal expected number of daily deaths in these areas. This predicted one-third increase in daily mortality is clearly a significant and preventable public health burden.

5. Willingness to Pay to Reduce Air Pollution in Ulaanbaatar

In addition to understanding the severity air pollution in Ulaanbaatar and the extent to which it affects people's health it is often useful for policy makers to realize how strongly people feel about spending resources to protect their health relative to other needs. This chapter reports on a survey of Ulaanbaatar residents designed to estimate their willingness to pay to reduce mortality risks. The study looks at mortality risk reductions of the magnitude and types typically resulting from air pollution reduction policy. The study asks residents about their willingness to pay for a 5- and a 10-in-1,000 annual risk reduction over a 10-year period (e.g., 5 in 10,000 annually). The study estimates that Ulaanbaatar residents are willing to pay approximately three percent of household income to achieve the 5-in-1,000 risk reduction. This implies a value of statistical life estimate of 319 million tugrug, or $221,000 based on the official exchange rate.

Introduction

People have many competing needs and desires. Knowing how much people in Ulaanbaatar are willing to pay (WTP) to reduce the kinds of health risks associated with air pollution can be helpful in planning how to address air pollution in the city. At the request of the AMHIB study Steering Committee, the World Bank study team conducted a survey estimating the WTP of Ulaanbaatar residents for reductions in health risks of the size and type that have resulted from air pollution policy improvements elsewhere.[8] This chapter reports the results of this survey.

Air quality improvements reduce the risk of both illness and death. Past studies have found that the WTP to reduce risk of death typically accounts for 85 to 90 percent of total WTP for reductions in health risks associated with air pollution (U.S. EPA 2006). As a result, this survey focused only on the WTP of Ulaanbaatar residents to reduce risk of death associated with air pollution. Air pollution can increase the risk of death immediately through its impact on those in the population who have more vulnerable respiratory and circulatory systems. It can also increase the risk of death in the future to the extent air pollution exposure causes or exacerbates diseases of the respiratory or circulatory system, or cancer. The survey asked about residents' WTP to reduce risks immediately and beginning at age 70. The size of the risk reductions were also of the magnitude typically seen in response to successful air pollution policy. The survey was administered to a random sample of Ulaanbaatar residents in January and February 2010.

Literature Review

The study team is aware of no prior Mongolian stated preference surveys measuring willingness to pay for reduction in mortality risk. It is also aware of only five such studies conducted in countries bordering Mongolia—all in China (World Bank 2009; Hammitt and Zhou 2006; Li et al. 2002; Wang et al. 2001; and Zhang 2002). All of these studies converted WTP into a value of statistical life (VSL) estimate. The value of a statistical life (VSL) is the average willingness to pay for a small reduction in individual mortality risk expressed in terms of risk to a population. If a population of 10,000 people experiences a

8 For further information about the WTP survey study, refer to Annex E to this report.

1/10,000 excess risk of mortality over a ten-year period, then statistically one extra person in the population would be expected to die during the ten-year period. This is what is meant by the loss of a statistical life. If the average person in a population of 10,000 people is willing to pay $600 for a 1/10,000 reduction in mortality risk, the VSL for the population is $6 million. Mathematically, VSL is the average WTP for a reduction in mortality risk divided by the reduction in the mortality risk. Estimates of VSL are used by decision makers around the world to help set policy priorities affecting health.

In the above five Chinese studies, mean WTP ranged from $32,000 to $64,000, implying VSL estimates that are quite low in comparison to those found in similar studies conducted elsewhere in the world. This likely reflects the fact that each of these studies had methodological problems (World Bank 2009).

In two phases from 2004 to 2009, a World Bank study team—made up of researchers from Resources for the Future (RFF) of Washington, DC, Fudan University in Shanghai, and People's University in Beijing—and the World Bank conducted a stated-preference study (i.e. a survey-based study where people are asked about their willingness to pay) in Shanghai, Chongqing, Nanning, and Jiujiang (World Bank 2009). The study used a survey instrument that had been successfully administered in six other industrialized countries prior to its administration in China (see annex E, table 12). This Chinese study estimated a mean VSL of $440,000 ($US 2008). Compared to other countries in which the survey had been administered, this estimate of Chinese WTP was lower in absolute terms than those in industrialized countries, but similar as a percentage of household income. Like respondents in Japan, Chinese respondents were willing to pay relatively more for future death risk reductions relative to reductions in immediate death risks than did respondents in the western countries surveyed.

Survey design and adaptation

The survey used in this study is based on one first developed for use in the United States (Alberini et al., 2004) and more recently adapted for use in China (World Bank 2009).

In adapting the survey for use in Mongolia, the study team had two fundamental goals. The primary goal was producing a survey that Mongolian respondents would understand well and accept and that would have risk reduction levels appropriate to air quality policy and would permit estimation of WTP appropriate for Ulaanbaatar. The secondary goal was to maintain as much consistency as possible with versions of the survey that had been administered successfully in other countries. This consistency will provide a stronger basis for judging the credibility of the Mongolian estimates.

After translating the survey into Mongolian, focus groups were used to identify changes needed to accommodate Mongolian cultural, sociological, and institutional conditions. These accommodations included accounting for the structure of health care delivery and adjusting the list of primary causes of mortality and the list of activities people engage in to protect their health. Ages, mortality rates, and WTP bids were changed to reflect Mongolian vital statistics and economic data. As in the U.S., Canadian, Chinese, and Japanese versions of the survey, respondents were offered a product that would reduce their mortality risk if used over a 10-year period. The product was described as having been approved by the relevant country's health authority. Based on focus group results, two risk reductions, 5-in-1,000 and 10-in-1,000, were chosen. Minor adjustments were needed in the way information on probability and risk was communicated in the survey. For example, the original survey used roulette to explain the concept of chance. Mongolian respondents were unfamiliar with roulette, but there is a widely viewed TV game that uses a similar wheel, so reference was made to that game rather than to roulette. Finally a risk-attitude question referring to air and train travel was changed to one related to crossing busy streets.

The Questionnaire

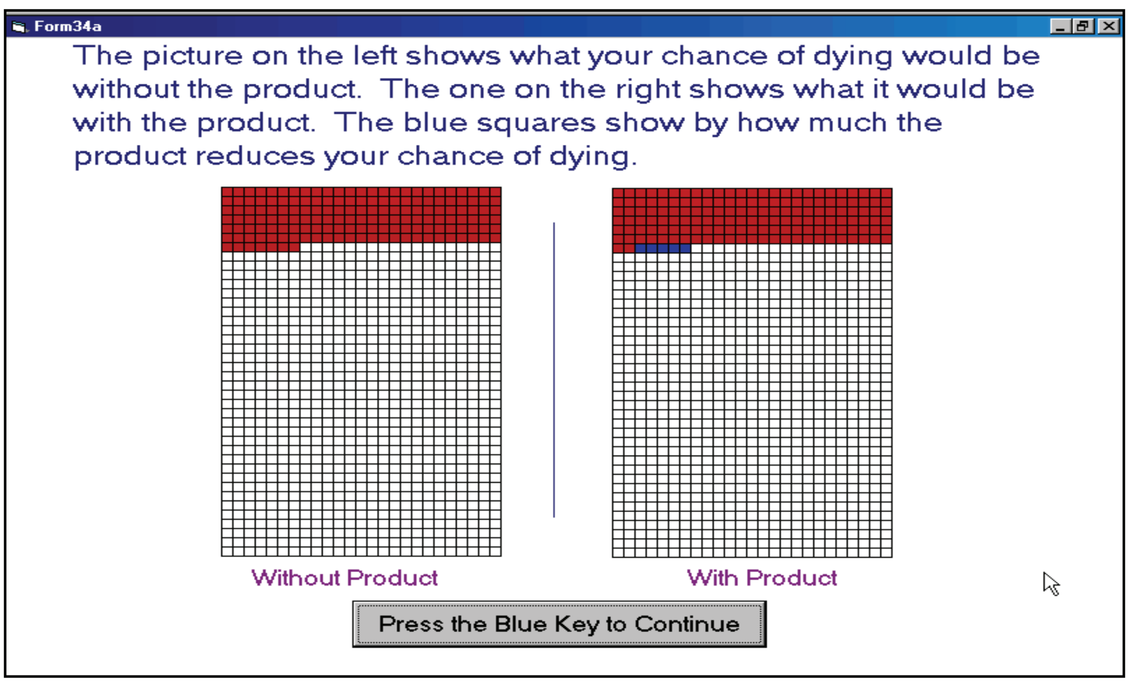
The questionnaire begins with demographic questions and asks respondents about their

health status and chronic disease history as well as that of their family members. The survey next introduces the concept of probability and the probability of dying or surviving. The survey then shows respondents how probability of dying will be represented in the survey and tests their understanding of this representation and the concept of probability in general (see figure 5-1). They are then presented information on age- and gender-specific leading causes of death in Ulaanbaatar and on common risk-reducing behaviors. The survey then presents information on the effectiveness and cost of common risk-reducing behaviors. Respondents are told the risk of dying of someone of their age and gender living in Ulaanbaatar and are asked to accept this risk as their own for the purpose of the survey. They are then asked about their WTP for mortality risk reductions of a given magnitude, occurring at a specified time. The survey ends with further demographic questions and debriefing questions that can be used to evaluate whether the respondent understood the survey and took it seriously.

The basic form of the WTP question asks how much the respondent would be willing to pay for a product that, when used and paid for over the next 10 years, will reduce baseline risk by *x* in 1,000 over the 10-year period. The latent risk reduction questions ask whether they would be willing to pay for a product that, when used and paid for over the next 10 years, will reduce their baseline risk by x in 1,000, for a ten-year period beginning at age 70 (see figure 5-2). The latent WTP questions are preceded by a question asking the respondents their perceived chance of surviving to age 70. This question encourages the respondent to think about their future and can be used to estimate discount rates.

As shown in table 5-1, the sample design has two treatments: in one, respondents receive a 5-in-1,000 risk reduction over 10 years as the initial question followed by a 10-in-1,000 risk reduction as the second question. In the other, respondents receive a 10-in-1,000 risk reduction and then a 5-in-1,000 risk reduction question. Respondents are asked two WTP questions.

Figure 5-1: Depiction of risk change (American version used to develop Mongolian survey)



Source: Authors' illustration.

Figure 5-2: Payment card elicitation of willingness to pay for a latent risk reduction (Mongolian version)

Source: Authors' illustration.

Table 5-1: Study Design (cumulative probabilities over a ten-year period)

Group of Respondents	Initial current risk reduction valued	Second risk reduction valued	
		Future risk reduction	*Current risk reduction*
		Age 40–65	Age 65 +
Wave 1 (N = 309)	5 in 1,000	10 in 1,000	
Wave 2 (N = 320)	10 in 1,000	5 in 1,000	

Source: AMHIB data.

The initial question is a contemporaneous risk reduction for all respondents. The second question is a latent risk reduction for respondents age 40 to 65 and a contemporaneous risk reduction for respondents over age 65.

The survey uses a payment screen to elicit WTP (see figure 5-2). This screen presents respondents with a matrix of ordered numbers (possible bid amounts) and asks them to pick the one representing their maximum willingness to pay for the risk reduction. Range intervals were designed to be roughly constant in percentage terms. Psychometric studies and experimental economics suggest this as a means of reducing response error (Rowe, Schulze, and

Breffle 1996; Ready, Navrud and Dubourg 2001).

The payment card elicitation approach (see figure 5-2) presents respondents with a matrix of ordered numbers and asks them to pick one corresponding to their maximum willingness to pay for the risk reduction. The chosen "stated" number can be thought of as (a) an appropriate estimate of WTP, (b) the top end of an interval between the chosen number and the next lowest number (which was estimated using a Weibull distribution), or (c) the bottom end of an interval between this number and the next highest number (which was not estimated). In order of conservativeness, the Weibull estimate, as called here, is more conservative (produces a lower WTP estimate) than the use of the stated value as an estimate. Alternatively, WTP is set at the value in the matrix immediately below the chosen number, which in this context is similar to a Lower Turnbull estimate. This would be the most conservative of the three estimates used in this analysis.

Administration of the survey

The survey was administered in Ulaanbaatar, the capital of Mongolia, using stratified random sampling by neighborhood. Respondents came to Neighborhood Family Health and Administrative Centers to take the survey. The survey was administered on weekends to accommodate respondents' work schedules. The survey was administered on laptop computers operated by trained enumerators. Enumerators all received the same training, including very explicit training regarding the level of interaction with respondents that was permissible to maintain consistency in administration across respondents. A sample of 629 respondents completed the survey. Participants were given a small gift for participating.

Data preparation and sample characteristics

In any stated preference survey, some responses cannot be taken as accurately representing a respondent's WTP. A respondent may fail tests of whether they understand the concept of probability or the way probability is presented in the survey. They may say they do not understand the survey. They may also bid an unrealistically high percentage of their income. Respondents who exhibit these criteria are typically eliminated from the sample. Table 5-2 reports observations targeted by these various cleaning criteria. The most common cleaning criteria met by respondents in this study (21 percent of respondents) was a respondent saying that he or she did not understand probability well (FLAG6). However, over 99 percent of the sample passed tests indicating that they had a basic understanding of the graphical way probability was presented in the survey.

Table 5-3 reports descriptive statistics of the full sample. Mongolia has a young population and a low life expectancy compared to other countries studied using this survey instrument. The sample similarly is skewed toward a younger population despite an effort to oversample in the older age categories.

Table 5-2: Descriptive statistics for cleaning criteria variables

Variable	Number obs.	% of total obs.
FLAG1*	6	0.95
OVER80**	1	0.16
FLAG6 ***	131	20.82
WTP/income $\geq$ 0.9	26	4.13

Note: *FLAG1 indicates a failure to pass tests of understanding of probability. **OVER80 identifies respondents who were over 80 years of age. ***FLAG6 indicates respondent said they did not understand the concept of probability.
Source: AMHIB data.

Table 5-3: Comparison of demographic variables by cleaning and place of birth

	Whole Sample	Cleaning approach C*	Comparison of means
Variable Definition	*Mean*	*Mean*	*Wald tests (p value)*
Socio-demographics			
Age	54.37	53.99	-0.61*(0.54)*
Age distribution (%)			
40–49	38	39	0.32 (0.75)
50–59	31	31	1.05 (0.29)
60–69	21	21	0.48 (0.63)
70 and older	10	9	0.32 (0.75)
Gender (1 = male, 0 = female)	0.38	0.40	0.71*(0.48)*
Share of respondents with university degree (%)	0.24	0.25	0.66*(0.51)*
Monthly Income (tugrug)			
Household Income	390,063	402,118	0.88 (*0.38)*
Per Capita Income	103,113	106,548	0.75 (*0.45*)
Observations	629	472	

Note: *Cleaning approach C drops Flag1, Flag6, Over80, WTP/income <0.9
Source: AMHIB data.

Eighty-three percent of the sample expects to live to age 70. Twenty-three percent of respondents report having problems with bronchitis and 44 percent have heart disease. The study sample is also more female than male (38 percent male). 45 percent of the sample have some college education. Mean monthly household income is 390,063 tugrug, or 103,113 tugrug per capita.

Estimation methodology

To estimate WTP and explain the factors that explain its variation, a model appropriate for interval data is used. The underlying econometric model is

$$\log WTP_i^* = X_i\beta + \varepsilon_I \qquad (1)$$

where *WTP** is the underlying willingness to pay for a selected risk reduction; *X* denotes a vector of age, health, and other attributes; β is a vector of coefficients; and ε is an extreme value Type I error term (Alberini et al. 2004). WTP estimates can be sensitive to the manner in which inconsistencies in responses and respondents who do not understand aspects of the survey are addressed. For the preliminary analysis presented in this chapter, the data using three alternative cleaning specifications is analyzed. Further details on estimation methods used in this study are provided in annex E.

Results

Table 5-4 reports the mean WTP results based on the three cleaning approaches. Cleaning approach A drops respondents who failed tests of probability understanding and who are over 80. Cleaning approach B drops these respondents and those who say they do not understand probability well. Cleaning approach C drops these respondents as well as those who say they would be willing to pay more 90 percent of their income for the risk reduction. Table 5-4 contains information on the WTP estimates in tugrug, both for contemporaneous and latent risk reduction, as well as Wald test statistics testing for differences in mean values among the various estimates. The preliminary analysis presented in this paper treats the chosen bid as the true WTP of respondents.

Table 5-4: External scope tests under alternative data cleaning approaches (respondents age 40–65)

	Sample A			Sample B			Sample C		
	Flag1 & Over80			Flag1, Flag6, Over80,			Flag1, Flag6, Over80, WTP/income<0.9		
	N	Mean		N	Mean		N	Mean	
Mean Value									
WTP5	303	169,274		232	173,772		221	159,457	
WTP10	319	185,721		260	194,481		251	185,717	
5 vs 10		-1.35*	0.09		-1.49*	0.07		-1.96*	0.03
WTP5_70	238	101,933		189	104,053		184	104,647	
WTP10_70	270	143,315		223	145,538		210	136,857	
5_70 vs 10_70		-3.41*	0.00		-3.17*	0.001		-2.58*	0.01
5 vs 5_70		5.84*	0.00		2.04*	0.02		4.36*	0.00
10 vs 10_70		3.41*	0.01		3.55*	0.00		3.63*	0.00

Note: Mean values are in tugrug. WTPx denotes an x in 1,000 reduction in risk of dying for the next ten years beginning immediately. WTPx_70 denotes an x in 1,000 reduction in risk of dying for ten years beginning at age 70.
Source: AMHIB data.

Certain regularities in response in WTP studies are expected based on basic economic theory. If these regularities are not observed, it raises questions about construct validity; that is, whether the survey instrument is effectively measuring respondents' WTP. For example, WTP for risk reduction should be increasing in the size of the risk reduction. Normally, one would also expect WTP for a risk reduction today to be higher than WTP for a latent risk reduction. This reflects a positive discount rate.

This survey design provides two tests of whether WTP responses increase with the size of the risk reduction. These are called scope tests. Does WTP increase with the scope of the benefit provided? This means, are respondents who received a 10-in-1,000 risk reduction over 10 years willing to pay more than those receiving a 5-in-1,000 risk reduction. The study finds that for each possible comparison, Ulaanbaatar respondents are willing to pay more for larger risk reductions. This effect is generally statistically significant for both contemporaneous and latent risk reduction.

The survey design also provides two tests of discounting by looking at the difference in WTP for a contemporaneous and latent reduction in risk where the size of the risk reduction is held constant. In table 5-4 all comparisons show as statistically significant and positive discounting.

Regression analysis provides further information on whether the survey is performing well. Standard economic theory indicates that WTP would increase with income and risk reduction. If health is viewed as a scarce good, then a history of poor health might also contribute to an increase in WTP for reduction of further health risks. In the case of latent risk reduction that starts at age 70, one would also expect that WTP is increasing in the respondents' subjective probability of living until age 70. In addition, several studies in the U.S. and China have found an inverted U-shaped relationship between age and WTP (see Alberini et al. 2004; Alberini et al. 2006).[9] Table 5-5 presents results of regression analysis on WTP for contemporaneous and latent risk reductions respectively.

[9] The exception is Itaoka et al. (2005), who conducted a contingent valuation survey in Japan, and found a positive linear effect from age, suggesting that WTP increases with age.

Table 5-5: Construct validity of WTP for the current and latent risk reductions (using a Weibull distribution)

Variable	Contemporaneous		Latent	
	Cleaning A	Cleaning C	Cleaning A	Cleaning C
Intercept	5.05***	2.19	3.15	1.63
Age	0.08*	0.07	0.12	0.11
Age square	-0.001*	-0.001*	-0.001	-0.001
University Education (=1)	0.19**	0.12	0.11	0.03
Gender dummy (1=male)	0.05	-0.02	-0.001	-0.02
Per capita monthly income (log form)	0.38***	0.60***	0.38***	0.52***
Born in Ulaanbaatar (=1)	0.19**	0.13	0.18**	0.05
Risk averse (=1)	0.17**	0.02	0.12	-0.08
Heart Disease dummy	-0.08	-0.05	-0.12	0.01
Bronchitis dummy	0.06	0.07	0.11	0.18
Cancer dummy	0.09	0.05	0.28	0.21
If the risk variable is 5 in 1,000 reduction	-0.03	-0.13*	-0.47***	-0.32*
Chance to survive to 70			0.005**	0.002
Scale parameter	1.08	1.26	1.06	1.16
Number of Observations	616	468	458	356

Source: AMHIB data.

Results for contemporaneous risk reduction show all the expected signs on explanatory variables. The relationships most central to the theory are those between income and WTP and risk reduction level and WTP. The coefficient for income is of the correct sign and both highly significant and large, and the one for risk reduction is significant once people who bid more than 90 percent of their income are dropped from the sample. This is consistent with scope test findings. The relationship between age and WTP for contemporaneous risk reduction shows the same inverted U-shape as found in some prior studies, but its significance is weak.

Regressions on WTP for latent risk reduction also show expected results. The coefficient on the 5-in-1,000 risk reduction over 10 years is significant and negative, indicating that respondents said they would pay less for a smaller risk reduction. The coefficient on respondents who thought they would be alive at 70 was also positive, but very small and only significant for cleaning approach A.

This study did not find strong evidence that people with bronchitis, high blood pressure, and cancer are willing to pay more to reduce mortality risk than those without. Theoretically, this relationship can be either negative or positive. Krupnick et al. (2000) found that these measures were either insignificant or had a positive effect on WTP in Canada and the U.S.

In our regressions gender did not turn out to be statistically significant. Thus, the WTP is not affected by whether a person is male or female.

Discussion

The overall conclusion from these tests and analyses is that respondents in Ulaanbaatar generally understood the survey and appeared to be giving valid responses about their WTP to

reduce mortality risk. That is, they appeared to take the survey seriously and gave responses that behave in the way one would expect based on economic theory and past studies.

This study produces WTP estimates for contemporaneous and latent mortality risk reductions. It also uses a variety of sample cleaning approaches and three different assumptions about how conservatively to interpret WTP. For policy analysis, the authors recommend use of the Lower Turnbull estimate of WTP to reduce contemporaneous mortality risk using sample cleaning approach C. They do so for three reasons. First, only results for cleaning approach C are presented because only estimates using this approach passed the most stringent of the validity tests. Second, proposed air pollution policy in Ulaanbaatar is likely to focus on reduction in particulate matter.

Finally, critics often claim that stated preference studies overstate WTP because respondents do not actually have to expend their own money and do not receive actual benefits. To address this concern, it is generally advisable to consider whether policies will pass cost-benefit tests when the most conservative estimates of WTP are used. The Lower Turnbull estimate assumes that the WTP amount provided by the respondent is the lower bound of an interval between this amount and the next higher amount on the payment card. As a result, the authors believe that a WTP of 159,000 tugrug for a 5-in-10,000 annual contemporaneous risk reduction is a reasonable reflection of preferences in this sample. This translates into a VSL of 319 million tugrug, or $221,000 based on the official exchange rate, or $493,000 based on a purchasing power parity (PPP) exchange rate.

PPP exchange rates are most often used in making cross-country comparisons. They are based on the price of a similar basket of consumer goods in different countries rather than currency exchange rates. Official exchange rates may be affected by capital flows not closely related to consumer preferences and may be influenced by government policy for macroeconomic reasons. Nevertheless, PPP rates can also be problematic, particularly for countries that are somewhat isolated and have unique cultures. Here, the ratio of internationally traded to non-traded goods would be low and it might be difficult to find a market basket of goods comparable to that used to compute PPP rates in other countries. Adjusting for quality differences of goods that appear to be in comparable categories can also be problematic. Therefore, dollar-denominated VSLs using the official exchange rate are also reported for Mongolia. For use in Mongolian policy analysis, the authors of this study recommend using either the value of statistical life estimates in tugrug or, if necessary, converted to U.S. dollars using the official exchange rate—simply because conservatism in this measure is desirable, given that there are so many uncertainties in the VSL estimates.

This value should be interpreted as only valid for Ulaanbaatar, not outlying rural areas of Mongolia. Even based on conservative assumptions, these results show that people living in Ulaanbaatar place a high value relative to their income on reducing their risks of death, a value comparable to that seen in other developed and emerging economies.

6. Current Health Costs of Air Pollution in Ulaanbaatar and Benefits from Management Scenarios

This chapter estimates the current health damages attributable to air pollution in Ulaanbaatar together with the health benefits (i.e. the avoided health damage) that potentially can be obtained from alternative management scenarios. The scenarios show how interventions targeting main sources of PM pollution in the city may reduce the population-weighted exposure, given alternative ambition levels of the interventions. The main sources looked at are ger household stoves, suspended soil dust, and heat-only boilers (HOBs). The scenarios reflect a 30 percent, 50 percent, and 80 percent reduction in the emissions from each of these sources separately and corresponding reductions for all sources together. Using exposure-response functions from epidemiological studies, the health effects associated with the different levels of pollution (today and for future scenarios) are estimated in terms of premature deaths, cases of chronic bronchitis, and hospital admissions. Using the estimated WTP for mortality risk reduction from chapter 5, and estimated unit costs for the other health end-points (chronic bronchitis and hospital admissions), the estimated health effects are monetized. The current health damage attributable to air pollution is estimated at 19.4 percent of Ulaanbaatar's GDP, and an 80 percent reduction in all main sources would yield a health benefit of 7.5 percent of the city's GDP. Achieving the air quality guidelines for Ulaanbaatar (50 μg/m³ for PM_{10} and 25 μg/m³ for $PM_{2.5}$) is estimated to yield a health benefit of 13 percent of the city's GDP.

Population-weighted exposure (PWE) at present and for 30 percent/50 percent/80 percent scenarios

In order to estimate health costs associated with the present Ulaanbaatar air pollution as well as their reduction as a result of pollution abatement scenarios, this report uses the *population-weighted average PM concentration*, which can be referred to in its shortened form as the *population-weighted exposure* (PWE). Compared to using the average annual concentration for the city, the PWE more accurately reflects exposure of UB's population to air pollution by taking into account the spatial distributions of the pollution and the population.

This section calculates the present health damage of air pollution, as well as the reduction of this damage as a result of some selected intervention scenarios. The costs related to the health damage, and the avoided costs (i.e. benefits) as a result of the interventions, are also calculated.

The scenarios are selected to show the range of effects of interventions on the two main source groups contributing to the PM concentrations and PWE—ger household heating systems and suspended soil dust, as well as on the heat-only boilers (HOBs), another fairly easily controllable source. The scenarios reflect 30 percent, 50 percent and 80 percent reduction in the emissions from each of these sources.

In this type of assessment of avoided health effects linked to an intervention, it is considered that the avoided effects and costs are annual for the year when the intervention has been fully implemented. These results are useful for comparing the effects situation before intervention (present situation) with the situation that will exist after full implementation of the interventions. In practice, an intervention is implemented over several years, with gradually reduced emissions, concentrations, and effects. When carrying out cost-benefit calculations to compare different types of interventions, the time line of the interventions should be taken into account, as well as integrated intervention costs and benefits (avoided effects costs) over the timeline, as is done in the cost-benefit analysis presented in chapter 9.

The PWE data in table 6-1 are used to estimate health benefits of the reductions. The data in the table are presented in figure 6-1. PWEs are calculated based upon the PM pollution maps presented in chapter 3.

The reduction in the PWE shows that ger area interventions provide the largest reduction, while interventions in dust suspension also provide significant reductions. The HOB intervention provides only a minor PWE reduction.

When interpreting figure 6-1, it is important to note that it represents the average PM concentrations (PWE). Portions of the population will still remain exposed to levels above the AQ standards even when the PWE does not exceed standard values.

Figure 6-1 shows the remaining PWE for PM_{10} and $PM_{2.5}$ under different emission reduction scenarios. The reductions drive the

Table 6-1: Population-weighted average PM concentrations (PWE) in Ulaanbaatar, and reductions from abatement scenarios, µg/m³

	PM_{10}	$PM_{2.5}$
Present situation (June 2008–May 2009)	**427.3**	**259.6**
Reductions in PWE from interventions:		
30% reduction of ger stoves	58.7	47.0
50% reduction of ger stoves	97.8	78.3
80% reduction of ger stoves	156.5	125.2
30% reduction of HOBs	2.7	1.6
50% reduction of HOBs	4.5	2.7
80% reduction of HOBs	7.1	4.3
30% reduction of suspended dust	49.3	14.8
50% reduction of suspended dust	82.2	24.7
80% reduction of suspended dust	131.5	39.5
30% reduction of all 3 sectors	**110.7**	**63.4**
50% reduction of all 3 sectors	**184.5**	**105.6**
80% reduction of all 3 sectors	**295.1**	**168.9**

Source: AMHIB data.

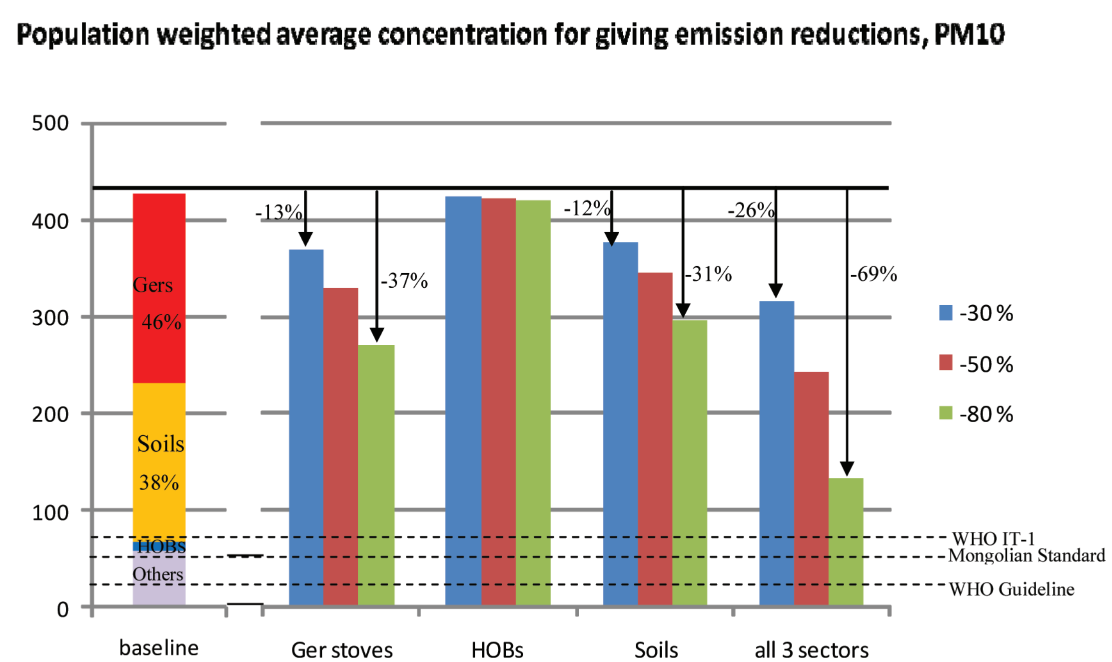
health cost calculations given in the next section. The figures indicate the present relative health impacts, and also the reductions in health impacts of different interventions, based on the spatial distribution of the population and of the PM sources and concentrations. For example, a 30 percent reduction in ger area emissions would result in a reduction in the population-weighted exposure of PM_{10} by about 13 percent and of $PM_{2.5}$ by 18 percent. Similarly, an 80 percent emission reduction in all the three sources in the figure would result in a PWE reduction of 69 percent for PM_{10} and 65 percent for $PM_{2.5}$. The total PWE is less than the emission reductions because the "other" sources (traffic, CHPs) are not reduced in this example. This PWE reduction does not, however, give a similar reduction in health costs due to the nonlinearity of health effects as a function of PM concentration. For example, a 30 percent reduction in ger area emissions yields a 5 percent reduction in calculated health costs, as shown in the next section.

Figure 6-1 shows that a larger reduction in emissions is needed to comply with the various AQ standards and guidelines. It should also be noted that even if the averaged population exposure meets an AQ standard, a substantial part of the population is still exposed to levels above the standard, because PWE is an average exposure.

Figure 6-1 shows that the WHO interim targets IT-1, at 70 μg/m³ for PM_{10}, can be met by reducing the three source sectors by more than 95 percent. The IT-1 target for $PM_{2.5}$, at 35 μg/m³, can only be met by also reducing the "other" sources, which include road traffic and the power plants (CHPs).

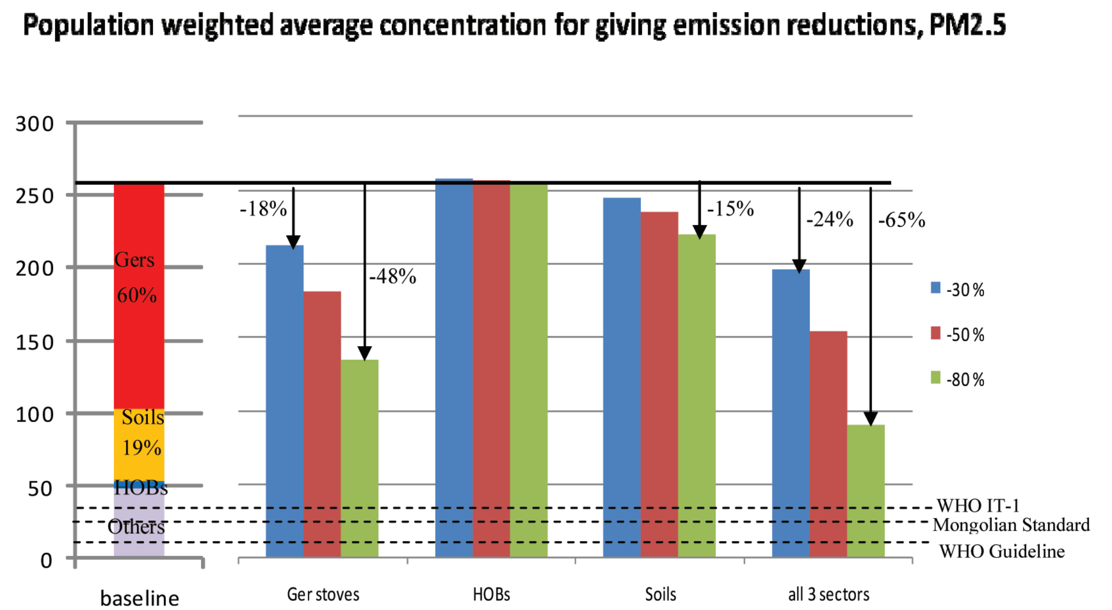
The Mongolian Air Quality Standards and the WHO guideline are more difficult to meet. The present situation regarding PM pollution in Ulaanbaatar is so extreme that emissions have to be reduced by about 95 percent, for all sources, to comply with these standards.

Figure 6-1: How much is air pollution reduced if emissions are reduced by 30%/50%/80%? PWE reductions for given emission reductions of PM_{10}



continued

Figure 6-1 *continued*



Source: Authors' illustration based on AMHIB data.

Avoided premature deaths, cases of chronic bronchitis and hospital admissions

A large number of studies around the world document a consistent association between elevated ambient PM_{10} and $PM_{2.5}$ levels and a variety of health end-points, such as respiratory infections, the number and severity of asthma attacks, the number of hospital admissions, school and work absenteeism, and mortality rates (OECD 2000). The health impacts from air pollution are determined by two main factors: (1) the concentrations of pollutants in the atmosphere, and (2) the number of people being exposed. A range of factors can modify the extent to which a given air pollutant affects a population, as for instance the general health status and co-exposure to other pollutants. In Ulaanbaatar, especially in the winter season, very high ambient PM concentrations occur in Ger areas, as evidenced by measurements, where the population densities are also high.

To calculate impacts of air pollution in Ulaanbaatar, this analysis applies the exposure-response functions used in the assessment of costs of air pollution in China by the World Bank (2007). The analysis includes the three major mortality and morbidity effect end-points associated with air pollution exposure: premature deaths (i.e. deaths brought forward due to air pollution exposure), new cases of chronic bronchitis, and hospital admissions for respiratory and cardiovascular diseases.[10] These are termed "health end-points." We estimate both the current excess number of cases—the number of cases that are attributable to current air pollution levels—and the number of cases that can be avoided by implementing the interventions described earlier.

Premature deaths and enhanced rates of chronic obstructive lung diseases (of which chronic bronchitis typically is the most prevalent) are two major health impacts associated with long-term exposure to PM pollution. Exposure-response relationships for these end-points are typically revealed by means of long-term cohort studies or cross-sectional studies (types of epidemiological studies). Enhanced hospitalization rates are found to be linked to air

[10] The exposure-response functions for chronic bronchitis, hospital admissions for respiratory and cardiovascular diseases (CVD) applied in WB (2007) is based on a meta-analysis of several Chinese studies (Aunan and Pan 2004).

pollution exposure on a shorter time-scale and are revealed in time-series studies.

Health impacts are estimated in physical and monetary terms in the following way:

First, a threshold value is set for PWE below which no health risks are assumed. The threshold value chosen could be the guideline value set by WHO or other international guideline values or local standards. WHO guideline values are typically determined by the level of pollution concentrations that are identified in epidemiological studies as "threshold" levels for observable effects. Thus, they are a metric for the actual physical impacts rather than what may be defined as the target or acceptable level in a specific setting. PM has no threshold level below which there are no effects. This study uses the annual average PM_{10} concentration of 15 μg/m³ as the lower threshold level for the effects, as was used by WHO in the Global Burden of Disease assessment (Cohen et al. 2004).

Second, the PWE values are combined with estimated baseline rates of the given health end-point in the population and exposure-response functions. This gives the estimated health impacts of exposure to excessive levels of ambient concentrations of PM. The AMHIB study includes a time-series study using data from a broad range of hospitals in Ulaanbaatar to evaluate the exposure-response relationship between incidences of hospital admittances for various respiratory illnesses and cardiovascular diseases (CVD) and ambient concentrations of PM in the city (see chapter 5). The study team applied the results from that study in terms of exposure-response functions for hospitalization as well as for current hospitalization rates for respiratory and cardiovascular disease in Ulaanbaatar.

Third, a unit cost value was estimated for each health end-point. For premature deaths and chronic bronchitis, the study team relied on results from the survey on the WTP of Ulaanbaatar residents (see chapter 6) to reduce risk of death associated with air pollution. For hospitalization cost estimates, a previous study in China was transferred (World Bank 2007).

Based on exposure-response functions from Ulaanbaatar (for hospital admissions) and from the literature (for mortality and chronic bronchitis), health impacts are derived using the following equation.

$$E = ((RR - 1)/RR)^* f_p {}^*POP$$

where E is the number of cases of each health end-point attributed to air pollution ("excess cases"), RR is the relative risk of health effect between two levels of pollution (here the current level and a lower level obtained from an intervention or the lower threshold level), f_p is the current incidence rate of the health effect, and POP is the exposed population considered. In the following, POP is assumed as the total population in Ulaanbaatar, which was 1.106 million in 2009. For hospital admissions $f_p{}^*POP$ is replaced with the actual annual number of hospital admissions. Except for the mortality function, where the study team relies on WB (2007) (which assumes a 15 μg/m³ PM_{10} as a threshold level), RR is given by:

$$RR = \exp(\beta^*(C - C_t))$$

where β is the exposure-response coefficient (see table 6-2 where betas are given as percentage values), C is the current pollution level, and C_t is the target pollution level obtained from an intervention or the assumed threshold value. We calculate the remaining number of cases attributable to air pollution after each intervention, and derive the number of cases that can be avoided by subtracting these figures from the calculated excess cases in the current situation (which is calculated by using the threshold levels described above). To determine costs of air pollution, and avoided costs as a result of an intervention (i.e., the benefits from reduced air pollution), this paper uses a willingness-to-pay methodology to monetize mortality and chronic bronchitis impacts and a cost-of-Illness methodology to estimate the economic value of avoided hospitalization (see World Bank 2007).

Due to the considerable attention these calculations may have when disseminated, it is necessary to provide some background in

academic literature to disclose key assumptions so that others could use this work and improve it.

An important reason for limiting the number of health end-points is the lack of background data in Ulaanbaatar relating to prevalence rates for different diseases, absenteeism from work and school etc. Despite this lack of data, assumptions are made in the following about the prevalence of chronic bronchitis in Ulaanbaatar. According to Lopez et al. (2006) the prevalence rate in China and Mongolia is around 3 percent in adults above 30 years of age, with large uncertainties in the estimate. The World Bank (2007) used a prevalence rate of 3.4 percent and a corresponding annual incidence rate (new cases per year) of 0.15 percent for China. This incidence rate was assumed in this report.

As mentioned earlier, the team used data for the total annual number of hospital admissions for cardiovascular and respiratory diseases in hospitals in Ulaanbaatar for the calculations related to these end-points. According to the AMHIB time-series study in Ulaanbaatar, the current baseline hospitalization rates for cardiovascular diseases and respiratory diseases are 0.0196 and 0.0685, respectively. This implies that a total of approximately 22,000 hospital admissions for cardiovascular diseases and around 76,000 hospital admissions for respiratory diseases in Ulaanbaatar are estimated on an annual basis. It is important to note that the hospital admissions estimates may not represent the entire effect related to these end-points because not all hospitals in Ulaanbaatar were included in the time-series study. However, some of the patients that were admitted to tertiary hospitals in Ulaanbaatar may not be residents of the city. This means that the number of avoided cases from interventions could be overestimated. Given that the patients at tertiary hospitals constitute only 12 percent of the total number, it is suggested that the net effect of the two uncertainty factors is not clear and could well cancel each other.

Because no long-term epidemiological cohort studies on mortality rates and air pollution have been carried out in Asia, the well-known, large study in the United States by Pope et al. (2002) was used by the WB (2007) to establish an exposure-response function[11]. A direct application of the exposure-response function in Pope et al. (2002) may lead to implausibly high damage estimates in polluted regions in Asia, and the U.S. results were therefore calibrated toward the few cross-sectional studies on mortality rates that were available for high pollution cities in China (World Bank 2007). The result is an exposure-response function that flattens toward higher PM_{10} levels. However, there are particularly large uncertainties related to this adjustment. New findings from short-term studies in Asia find that the exposure–response functions appear linear over a fairly large range of ambient concentrations up to and sometimes exceeding 100 $\mu g/m^3$. However, in a recent study from the U.S. (Pope et al. 2009) a comparison of exposure-response relationships between urban ambient particulate matter, passive cigarette smoking, and active cigarette smoking demonstrates a logarithmic exposure-response relationship with ischemic heart disease, cardiovascular disease, and cardiopulmonary disease.[12]

The study includes exposure levels far exceeding the levels typically encountered in urban settings—both in developed and developing countries—but conversely includes the levels encountered in Ulaanbaatar. The findings in Pope et al. (2009) support the use of nonlinear exposure-response functions. In addition to the estimated premature deaths resulting from the adjusted exposure-response function in World Bank (2007), this report provides an estimate of the health effect using that exposure-response function from Pope et al. (2009). This will indicate to some extent the sensitivity to the final

[11] Note, however, that in the analysis of the warm season in Ulaanbaatar in the time-series study described in chapter 5 in this report, a relationship between $PM_{2.5}$ and all-cause mortality was found. Specifically, a 10 $\mu g/m^3$ change in $PM_{2.5}$ was associated with a 1.38 percent change in mortality. This estimate is similar to those reported from studies of $PM_{2.5}$ in the U.S. In our view, the finding on a short-term effect on mortality in Ulaanbaatar lends credence to a long-term exposure effect on mortality in the city. Thus, we suggest it is reasonable to assume that the long-term exposure studies used here are relevant also to Mongolia.

[12] The study by Pope et al. (2009) uses estimated daily dose as the exposure variable. Daily dose (DD) is estimated from concentration levels by assuming an inhalation rate (IR) of on average 18 m^3/day for adults, i.e. in the present calculation we assume DD = PWE×IR. The highest dose for passive smokers in the study corresponds to 50 mg/m^3, while the lowest dose for active smokers in the study corresponds to 1000 mg/m^3.

results of the choice of function for the mortality impact.

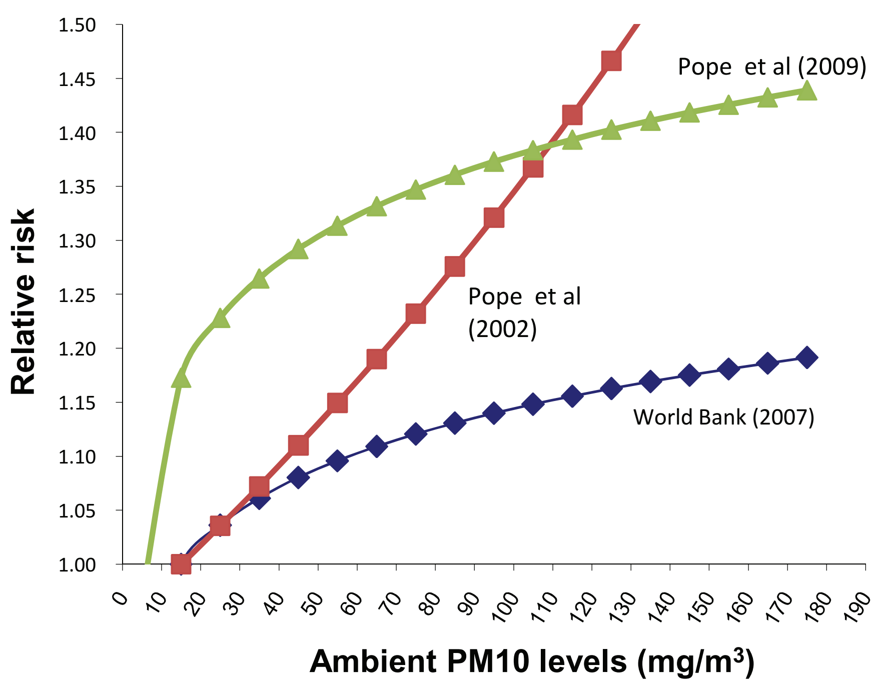
When applying the function from Pope et al. (2009), a threshold level for PM_{10} is not inserted, because the team considers it more correct to use the original nonlinear function in the calculation. Again, it is necessary to note that the relationship between the two estimates—derived from using the World Bank (2007) function and the Pope et al. (2009) function)—differs across abatement options. This is because the WB function uses PM_{10} values while the Pope et al. (2009) function uses $PM_{2.5}$, and the ratio between PM_{10} and $PM_{2.5}$ varies across the different abatement measures. The relative risk estimates obtained by applying, respectively, the exposure-response function from WB (2007), Pope et al. (2009), and Pope et al. (2002) are shown in figure 6-2. RR estimates obtained from using Pope et al. (2009) are higher when compared to the estimates from WB (2007). However, the slopes of the two curves are not very different at high levels of PM_{10}.

As carried out in previous applied studies (Mestl et al. 2004; Kan et al. 2004), the report uses the population-weighted exposure (PWE) estimates for the whole region (i.e. the concentration times population in each grid averaged for the total population in all grids) as input to the health benefit analysis. Given that the exposure-response functions for mortality are nonlinear, the results probably deviate slightly from the results that would have been obtained using geographically disaggregated PWE values. This uncertainty, however, is regarded by the team to be minor compared to other uncertainties in the analysis.

Monetized health benefits

To assess the unit costs of a premature death, this report relies on the willingness-to-pay study carried out as part of the AMHIB study (see chapter 5) which derived a value of statistical life (VSL) of $221,000 i.e. the value placed on avoiding premature death. As in WB (2007)

Figure 6-2: Relative long-term mortality risk associated with different levels of PM_{10}, estimated using three different functions



Source: World Bank (2007), Pope et al. (2002), and Pope et al. (2009).

this value is multiplied with 0.32[13] to obtain an estimate of the WTP for avoiding a new case of chronic bronchitis (see table 6-2). Unit cost estimates for hospitalization are derived based on WB (2007). The report uses the ratio between the value placed on these end-points for China by WB (2007) and the GDP/cap in China combined with the GDP/cap of Mongolia in 2008 to calculate the corresponding unit cost estimates for Mongolia.[14]

Table 6-3 shows the current estimated number of cases attributable to PM pollution and the number of cases that can be avoided from implementing the interventions described earlier. It also shows the monetized health impacts. The current health damage corresponds to 18.8 percent of GDP in Ulaanbaatar and 8.8 percent of GDP in Mongolia[15] in 2008. In the sensitivity calculation using the exposure-response function from Pope et al. (2009), current damage corresponds to 27.9 percent of GDP in Ulaanbaatar and 13.1 percent of GDP in Mongolia. The difference in the estimated health damage derived from the use of two different exposure-response functions indicates the substantial uncertainty in the health damage assessment. However, it is clear that health damage is also substantial.

13 This factor is derived from a study (Viscusi et al. 1999) indicating that people's choices imply that the utility of living with chronic bronchitis is about 0.68 of the utility of living in good health (Viscusi, W.K., W. Magat, and J. Huber 1991. "Pricing environmental health risks: A survey assessment of risk-risk and risk-dollar tradeoffs for chronic bronchitis." Journal of Environmental Economics and Management 21:32–51.)

14 I.e. Unit cost (Mongolia) = [Unit cost (China)/GDP per cap (China)]*GDP per cap (Mongolia).

15 GDP in Mongolia was $5.258 billion in 2008, in current USD (WB database, for 2008, available: http://econ.worldbank.org/WBSITE/EXTERNAL/EXTDEC/0,,menuPK:476823~pagePK:64165236~piPK:64165141~theSitePK:469372,00.html). We assume the ratio between GDP in Ulaanbaatar and GDP in Mongolia is the same in 2008 as in 2007, i.e. 0.47.

Table 6-2: Exposure-response coefficients (% change in incidence of health effect per μg/m^3 PM_{10}), baseline annual incidence rates, willingness-to-pay (WTP) for avoiding premature death (long-term effect) and new cases of chronic bronchitis, and cost of illness (COI) of hospital admissions

Health end-point	Exposure-response coefficient (PM metric)	Baseline incidence rate	(USD per case)
Premature death (WB method)	See WB (2007)	0.0067	221,000 (WTP)
Premature death	see text	0.0067	221,000 (WTP)
(Pope et al. (2009)			
Chronic bronchitis	0.48 (PM_{10})	0.0148	70,720 (WTP)
Respiratory Hospital admissions	0.024 ($PM_{2.5}$)	0.0685	1,055 (COI)
CVD Hospital admissions	0.082 ($PM_{2.5}$)	0.0196	1,703 (COI)

Source: AMHIB data.

Table 6-3: Estimated current health damage due to PM pollution in Ulaanbaatar (base case), number of cases avoided due to interventions, and monetized current cost and benefit from interventions (in mill USD)

	Annual number of cases				Monetized (mill USD)							
	All-cause mortality (chronic)	Chronic bronchitis	Hospital admissions (Respiratory disease)	Hospital admissions (CVD)	All-cause mortality (chronic)	Chronic bronchitis	Hospital admissions (Respiratory disease)	Hospital admissions (CVD)	SUM (mill USD)	Share of GDP in UB (2008)	SUM (mill USD) (sens.)	Share of GDP in UB (2008) (sens.)
Base case (current health damage)	**1591 (386 - 2721)***	**1411 (1219 - 1516)***	**4465 (1828 - 8083)***	**4063 (2290 - 6122)***	**352 (85 - 601)***	**100 (86 - 107)***	**4.71 (1.93 – 8.52)***	**6.92 (3.90 – 10.43)***	**463 (176.83 – 726.95)***	**18.8 % (7.18 – 29.52)***	**687**	**27.9%**
30% reduction of ger stoves	**63**	**74**	**619**	**528**	**14**	**5**	**0.65**	**0.90**	**21**	**0.8 %**	**22**	**0.9 %**
50% reduction of ger stoves	**112**	**136**	**1035**	**889**	**25**	**10**	**1.09**	**1.51**	**37**	**1.5 %**	**40**	**1.6 %**
80% reduction of ger stoves	**198**	**253**	**1663**	**1444**	**44**	**18**	**1.75**	**2.46**	**66**	**2.7 %**	**74**	**3.0 %**
30% reduction of HOBs	**3**	**3**	**28**	**24**	**1**	**0**	**0.03**	**0.04**	**1**	**0.0 %**	**1**	**0.0 %**
50% reduction of HOBs	**4**	**5**	**47**	**40**	**1**	**0**	**0.05**	**0.07**	**1**	**0.1 %**	**1**	**0.1 %**
80% reduction of HOBs	**7**	**8**	**75**	**64**	**2**	**1**	**0.08**	**0.11**	**2**	**0.1 %**	**2**	**0.1 %**
30% reduction of suspended dust	**53**	**60**	**520**	**443**	**12**	**4**	**0.55**	**0.75**	**17**	**0.7 %**	**10**	**0.4 %**
50% reduction of suspended dust	**92**	**109**	**868**	**744**	**20**	**8**	**0.92**	**1.27**	**30**	**1.2 %**	**18**	**0.7 %**
80% reduction of suspended dust	**159**	**199**	**1395**	**1205**	**35**	**14**	**1.47**	**2.05**	**53**	**2.1 %**	**30**	**1.2 %**
30% reduction of all 3 sectors	**129**	**159**	**1172**	**1009**	**29**	**11**	**1.24**	**1.72**	**43**	**1.7 %**	**36**	**1.4 %**
50% reduction of all 3 sectors	**246**	**322**	**1964**	**1714**	**54**	**23**	**2.07**	**2.92**	**82**	**3.3 %**	**69**	**2.8 %**
80% reduction of all 3 sectors	**522**	**707**	**3169**	**2822**	**115**	**50**	**3.34**	**4.81**	**174**	**7.0 %**	**144**	**5.8 %**

Note: Sensitivity estimates using Pope et al. (2009) for mortality impacts.
* These intervals were calculated based on the 95% confidence interval of the estimated dose-response coefficient and a +/- 30% interval of the PWE values. The lower (higher) value represents the estimate using the lower (higher) ends of both the 95% confidence interval of the dose response coefficient and PWE concentration. Similar confidence intervals apply to the estimated health damage reductions in the various scenarios but are not displayed here for the sake of clarity of presentation.
Source: AMHIB data.

The maximum achievable benefit (80 percent reduction in all 3 sectors) corresponds to 7.0 percent of GDP in Ulaanbaatar in 2008 (3.3 percent of GDP in Mongolia). In the sensitivity calculation this figure receives 6.2 percent of GDP in Ulaanbaatar (2.9 percent of GDP in Mongolia). These sensitivity estimates are lower than the base case, while the total damage sensitivity estimates are higher because of the shape of the two exposure-response functions that are applied to calculate mortality impacts in the base case and in the sensitivity case, respectively, as well as the exact profile of the abatement options involved. This is because the $PM_{2.5}/PM_{10}$ ratio is *not* constant across abatement scenarios. If the $PM_{2.5}/PM_{10}$ ratio of the source that is subject to abatement is high, the ratio of the calculated benefit in the sensitivity case versus the base case will be relatively higher than in a case when the $PM_{2.5}/PM_{10}$ ratio is low.

It should be noted that in this type of assessment of avoided health effects linked to an intervention, it is considered that the avoided effects are annual for the year when the intervention has been fully implemented. These results are useful for comparing the effects situation before intervention (present situation) with the situation that will exist after the interventions. In practice an intervention is implemented over several years, with gradually reduced emissions, concentrations and effects. When carrying out cost-benefit calculations to compare different types of interventions, the time line should account for the interventions, as well as integrate intervention costs and benefits (avoided effects costs) over the timeline. In chapter 8, such an assessment is carried out for some selected abatement options.

While the estimated health effects from PM pollution in Ulaanbaatar presented here are significant, it should still be noted that the calculations do not take into account the exposure to indoor air pollution in gers. Enhanced PM levels indoors in ger households dependent on solid fuels for cooking and/or heating (assumed to be high for the short periods of time of lighting phase) could imply that PWE values may in fact be even larger than estimated in this report.

7. Air Pollution Abatement Options and Their Costs in Ulaanbaatar

Main findings

Comparing different scenarios can be useful in examining potential costs and PM_{10} reduction impacts of selected PM reduction measures. In addition to the baseline scenario, alternative scenarios include (1a) reducing start-up emissions through backlighting the fire; (1b) reducing start-up emissions through slight modifications of the stove; (2) replacing existing stoves with cleaner coal stoves, without changing the fuel; (3) replacing existing stoves and fuels with cleaner stoves and semi-coked coal fuel (SCC); (4) installing electric heating in existing ger homes; (5) relocating ger households into apartments; (6) installing heat-only boilers; and (7 and 8) controlling fugitive dust (paving roads and greening the city).

A short-term measure (scenario 1a) of reducing the startup emission of stoves through changing lighting methods has a negative NPV of $463 per ton of PM_{10} reduced. Another short-term measure (scenario 1b) of reducing the startup emission of stoves through modification of stoves in addition to a change in the lighting method, also has a negative NPV of $208 per ton of PM_{10} reduction. These two scenarios also reduce a substantial amount of PM_{10} in an absolute term. The long-term measures such as apartment relocation and electric heating, which require a large infrastructure investment, have much higher NPV per ton of PM_{10} reductions.

Ger area emissions reduction options and their costs

Introduction

The study team has explored the impact and cost-effectiveness of different options to reduce particulate emissions. The scenarios follow portions of the Mongolian Government's "Smokeless UB" proposal, albeit with some modifications based on the acquired experience during the preparation of the UB Clean Air Project (UBCAP project, to be financed by the World Bank) and overall dialogue with government agencies and donors since mid-2007, when the World Bank started its work on air pollution in Ulaanbaatar. One of the main differences is the increase in balanced short, medium, long term measures in the discussed scenarios, while the Smokeless UB proposal had a program with a shorter time-span. In addition, the analysis and scenarios mainly focus on ger area heating issues.

As this section may attract considerable attention in Mongolia, it is necessary to discuss the limitations of the estimates. At the time of writing this final report, the capacity to measure the impact of emission reduction measures in UB had only recently been established. Ambient emission levels can easily be measured in UB, and have in fact been monitored for a number of years. However, measuring the impact of mitigation measures at the level of the various

individual sources of pollution (cars, CHP plants, ger stoves, HOB, etc) requires special expertise and equipment. As a first step, a state-of-the-art laboratory was established in UB in August 2010 by the Ministry of Mineral Resources and Energy with the financial support of the Asian Development Bank and technical support from the World Bank. This laboratory is able to measure the absolute level of emissions in the smokestack of a stove (the main source of pollution), as well as the reduction in emissions from the various types of modifications (to the stoves and the fuels). Before the establishment of this laboratory, such measurement capacity did not exist and was one of the barriers to predicting the effect of specific measures and, thus, the overall development of effective mitigation measures for ger heating systems. The laboratory has only recently started to operate regularly.

Some types of interventions have a relatively more straightforward impact. For example, when ger area households move into apartments, under certain assumptions, it is possible to reduce to nearly zero the contribution of ger household heating to harmful ambient concentrations of PM. This assumes that the new CHP plant should be constructed to accommodate the heat load, that it operates good emission control equipment and manages its waste (ash ponds) appropriately—all of which would need to be verified. It could be assumed, as an initial estimation, that the end-use emission reductions would be nearly 100 percent.[16] Households would likely abandon their ger stove and would use district heating from the CHP plant.

However, although the absolute levels of emissions from ger stoves have been measured, more measurements are needed to chart the results with more confidence. The initial measurements show that a well-operated traditional stove emits more than 300 mg of $PM_{2.5}$ per MJ of heat produced. This contrasts with the measurements of a number of clean stoves that showed a range of 1–10 mg of $PM_{2.5}$ per MJ of heat produced. The $PM_{2.5}$ emission reduction therefore could exceed 95 percent if these cleaner stoves are used on a large scale. However, it must be noted that, although some stoves submitted for testing to the laboratory were called "clean," they performed equally with traditional stoves leading to the conclusion that not all "clean" stoves are actually clean. This justifies the existence of the laboratory as an unbiased method to determine the actual performance of the stoves as a first step, although the performance needs to be verified when households use the stoves outside of the laboratory environment. In a second-order estimation, the addition of apartments will increase the load for electricity and heat and because the three CHPs are currently close to the maximum capacity, additional capacity is needed. A new plant means that more coal will be burned in the valley, resulting in increased emissions. However, this level of analysis is beyond the scope of the current exercise, and on a household basis the emissions from coal stoves far exceed the emissions from the CHP system.[17]

The impact of different stoves and different fuels is more difficult to determine. Combined stove-fuel combustion/emission testing is necessary to check the effects of prevailing combinations. Particulate emissions are the result of poorly performing heating systems (stove-fuel combinations and fuel consumption). Improving the combustion characteristics of the stove can reduce emissions. Such reduction requires changing or modifying the stove. Behavioral changes, such as the way households light their stoves, can also lead to

16 This assumption does not consider a resulting increase of PM10 and other pollutants from power generation as a first-order approach of the issue. CHP plants supply heat and electricity to industries and households. The effect of the incremental number of apartments on the total emissions for all users combined initially remains small. However, this would need to be studied in more detail to determine the incremental emissions due to the increased electricity or DH load. Compared to the emission reduction from not using coal in a heating stove, these can be ignored in the first-order approach.

17 In addition, the government of Mongolia has been initiating a 100,000 Solar Ger Program. The World Bank is supporting this program through the Renewable Energy and Rural Electricity Access Project by assisting in increasing access to electricity and improving the reliability of electricity service among the herder population and in off-grid soum centers with solar home systems (SHSs). The project will contribute 65,400 of the 98,322 total SHSs supplied as a part of the GoM 100,000 GER Program. While the project focuses on rural areas, this may partly, though not significantly, offset the increased air pollution.

emission reductions.[18] At the time this report, the MMRE's laboratory had tested about 10 different stove models, all with Nalaikh coal due to lack of availability of other types of fuels. The more promising test results have been used in this scenario analysis. A baseline emission factor was established for a traditional stove using traditional fuel, and its operation simulated as closely as possible in a traditional manner.[19] The following section discusses emission reductions *relative to* the baseline (i.e. relative emissions reductions). Due to the considerable attention paid to fuel switching, especially to semi-coke coal products, estimates of combustion characteristics have been assumed. For the AMHIB analysis, estimated relative emission reductions are used that will be verified more precisely through absolute emission level measurements when they are available from the UB laboratory.

The analysis presents the following individual options, with each leading to a scenario in which the option is rolled out on a large scale. It is possible to combine the options to look for higher performing scenarios:

Baseline; business as usual

Scenario 1a: Reduce start-up emissions through backlighting the fire

Scenario 1b: Reduce start-up emissions through slight modifications of the stove

Scenario 2: Replace existing stoves with cleaner coal stoves, without changing the fuel

Scenario 3: Replace existing stoves and fuels with cleaner stoves and SCC

Scenario 4: Install electric heating in existing ger homes

Scenario 5: Relocation of ger households into apartments

Scenario 6: Heat-only boilers

Scenarios 7 and 8: Control fugitive dust (paving roads and greening the city).

Scenarios 6, 7, and 8 are discussed in the following two sections, as they do not deal directly with ger household heating issues but do have an impact on emission levels in Ger areas.

The first five scenarios reduce the emissions from space heating in ger areas, the sixth reduces emissions from HOBs, and the last scenarios reduce emissions from fugitive dust. For each of the above intervention scenarios, the cost of realizing the action has been estimated as well as the incremental benefits, relative to the baseline situation. The goal of this analysis is to indicate which of the intervention scenarios are the more cost-effective and faster. It is possible to analyze many combinations of different interventions using this framework. The five scenarios below, therefore, are intended to illustrate how various measures could be compared and prioritized for government support and policy making. This analysis initially does *not* look at the resulting benefits, only at the costs needed to realize each of the scenarios for reducing emissions. Benefits can initially be assumed to be approximately equal in terms of health benefits, and will be identified in detail later in other chapters.

Description of the scenarios

The five scenarios, particularly the expected outcome and what is needed to achieve it, are described in more detail in the following.

- **Baseline; business as usual.** This describes the status quo as observed today with several trends expected to continue: (a) growth of the city through natural population increase and a large influx of migrant workers from the country side; (b) conversion of moveable ger dwellings into fixed wooden and brick homes; and (c) relatively fast growth of low-pressure boilers and decreased use of simple stoves (with or without heating wall), which increases coal consumption.
- **Scenario 1 (short-term).** Reduce start-up emissions. This is a promising option that was

[18] Measurements in a qualified laboratory in Johannesburg, South Africa, and recently (November 2010) confirmed in MMRE's Ulaanbaatar laboratory, indicate that it is possible to obtain emission reductions of 80 percent or more from such behavioral changes.

[19] Testing protocols are expected to be available at the laboratory.

first described in the World Bank's Mongolia: Heating in Poor, Peri-Urban Ger Areas of Ulaanbaatar (further discussed as "Ger Heating Report", World Bank's Asia Sustainable and Alternative Energy Program, October 2009), the Air Pollution in Ulaanbaatar Initial Assessment of Current Situation and Effects of Abatement Measures (World Bank 2009), and was further considered by Prof. Lodoysamba at the National University of Mongolia. It has become apparent that most of the emissions come from the cold start-up phase of the stove and to a lesser extent from the refueling. Measurements confirmed that PM emission reductions of 60 to 80 percent can be obtained when the fire is started differently and when the fire is not allowed to die down but continues to burn throughout the day and night. This scenario thus reflects mainly behavioral changes and not necessarily large capital investments for the beneficiary. There are two options to reduce the start-up emissions:

a. The first is to light the fire in a different manner. The fire is usually lit at the back of the stove, toward the chimney. Instead of using wood, another fuel such as LPG is recommended to start the fire; simple LPG canisters can easily be used and are available already in ger areas.
b. The second is to slightly modify the stove and use the back-lighting method of starting the fire. The design of the stove can be changed in by inserting more firebricks into the stove. This will reduce the size of the combustion chamber and result in a slower and cleaner burn resulting in fuel savings of some 15 percent. The starter fuel and the bricks are part of the cost for rolling out this scenario, and therefore a publicity/promotional program to convince households to start and continue using a different firing technique would be required. The main issue to address in this scenario is the training and awareness program.[20]

[20] Some measurements have now been conducted in UB during the ADB-supported Clean Air Policy Advisory Support and Technical Assistance Project; however, the measurements should be confirmed through additional testing.

- **Scenario 2 (short-term).** Replace existing stoves with new coal stoves ("cleaner stoves") without changing the fuel. Although several models of emission reducing stoves exist, not all combinations have been tested. Of those tested, measurements indicate that the right type of stove with a traditional fuel (nalaikh coal) can achieve relative reductions in excess of 95 percent. In addition, fuel savings of up to 50 percent have been observed and the stove may remain hot for much longer periods (one model stays warm for over 10 hours). In partnership with the World Bank and GIZ, the Ministry of Mineral Resources and Energy's (MMRE's) Clean Air Project supported by the Asian Development Bank (ADB) is spearheading this activity, with the establishment of the laboratory, the training of stove designers, and a pilot program to test some more promising stove models. This scenario refers to an effort to make cleaner stoves available to users on a large scale. Successful implementation would require (a) an awareness campaign to convince households of the advantages of changing their stove; (b) a financing mechanism with a possible subsidy component to enable households to purchase the stove as well as to promote a wide variety of eligible stoves to address customer preferences and increase chances of rapid market penetration; and (c) an eligibility program to select the appropriate stoves for support and dissemination, and to create a sustainable production capacity of such stoves. The main issue with adoption of this scenario will be the perceived benefits from the stove to the user. The likely questions include: "Does it save fuel? How quickly does it give off heat, and is cooking within accustomed times and methods possible? How often is refueling needed? Does it smoke when opening the door for refueling? How much does it cost?" The costs of realizing this scenario will include the investment in new stoves, the replacement of these stoves after their useful service life, removal of old stoves, a publicity/promotional program, a quality control mechanism to maintain a sustainable production capacity of these stoves, and a possible subsidy that might be required for

quick adoption. The new stoves will reduce fuel consumption and thus provide a benefit to end-users. Another economic benefit for this scenario is a reduction in implementation costs.

- **Scenario 3 (medium-term).** Replace existing stoves and fuels. Semi-coked coal (SCC) receives much attention, and while SCC can burn cleanly in an appropriate stove, there are two challenges associated with this scenario. SCC is difficult to light and its production costs are higher than raw coal. Raw coal burns very cleanly after the start-up phase and actually transforms into coked coal with associated low emissions. The bulk of emissions occur during the start-up phase. Since semi-coked coal is difficult to ignite due to the absence of volatiles, wood and other start-up fuels are needed, which promote high emissions. Moreover, because the cost of producing semi-coked coal is high, the heating costs associated with the converted fuel are much higher than with raw coal, and equalization payments (subsidies) are necessary to avoid poor households paying more for heating. Since start-up emissions constitute most of the total emissions, the overall impact remains unclear if more wood is needed to get the fire started compared to raw coal. Tests so far have been inconclusive as to whether SCC will reduce emissions. Furthermore, it is necessary to use new stoves to burn SCC cleanly. Because SCC is more expensive than raw coal, the European Bank for Reconstruction and Development (EBRD)'s Clean Air Initiative has proposed a continuation of equalization payments until scale economies can be obtained and SCC could be sold without subsidies. This scenario still requires additional basic research to develop the emission details, and therefore the study team needed to assume certain benefits that could be verified later. The scenario therefore includes setting up the production capacity of SCC and SCC stoves, an awareness campaign to convince people to start using it in new stoves, and recurrent annual subsidies to enable the use of SCC at equal costs to raw coal. The industrial production of semi-coked coal from raw coal requires a commitment by the government to recurrent fuel consumption subsidies until the economies of scale are achieved and/or incomes rise to afford the more expensive fuel. Therefore, the benefits need to be confirmed conclusively before a program is started.
- **Scenario 4 (medium-term)**. Install electric heating in existing ger homes. This approach is discussed in more detail in the *Ger Heating Report* (World Bank/ASTAE 2009). This requires a large investment program to create the capacity to generate the power needed to supply ger households with electricity for heating (estimated at 1.7 GW by MMRE in 2011). In addition, an equalization charge is needed because the cost of electric heating is significantly higher than the cost of heating with coal. In this option, people do not move into new homes but continue to live at their current residence and start using electric stoves for heating and cooking. The cost of electric stoves and heaters, the cost of electricity minus the savings of coal fuel, and the cost of infrastructure for incremental generation and distribution capacity will need to be incorporated into the cost analysis. The emission reduction can be large (close to 100 percent; see also remarks on apartment buildings[21]), assuming that people will actually refrain from using coal once they obtained an electric heater. A limiting factor will be the infrastructure investments to supply the additional electricity and the willingness of households to pay for the electricity, because although electric heating is more convenient than coal heating it will also be more expensive (or, a subsidy may be needed to equalize heating costs, but this has not been incorporated for now). The scenario assumes that most people in ger districts will actually switch to electricity once the government announces the availability of this option.
- **Scenario 5 (long-term)**. Relocation of ger households into apartments. This is the preferred long-term option, indicated in the Smokeless UB program. New apartment buildings are established in newly developed

[21] The incremental emissions at the CHP plant have been ignored in a first-order estimation.

areas, in existing ger areas, and in other cities. The impact is relatively simple, as coal consumption can be avoided almost completely (from heating in coal stoves). There will be an increased contribution from the district heating system, but this is estimated to be small compared to the consumption of coal used for heating in ger stoves. The costs of construction, as well as the incremental capacity needed for district heating, will need to be incorporated in the cost analysis, and these costs are very high.

Results—cost implications

The absolute level of impact on emission reductions cannot be measured yet in all cases. As a result, the reduction is expressed in percent of the baseline, i.e., compared to as if no intervention had taken place and trends would have continued while business as usual takes place. The emission reductions over time are then compared to the costs needed to realize these reductions.

The costs for the intervention include the following types of investments and expenditures (see table 7-1).

- Cost of the program to promote the intervention (publicity campaign, training, including any subsidy needed, cost of testing and certification)
- Cost of additional equipment needed (such as stoves, electric heaters, apartment building, etc.)
- Cost of additional infrastructure needed (additional production capacity of clean fuels, electricity and/or heat, electricity/heat distribution network)
- Cost of incremental heating energy (or saving, whichever applies; in the case of apartments, coal and firewood saved, but electricity and district heating energy is used instead)

The net present value of the identified costs and possible direct benefits (fuel savings) are then calculated for the period 2010–2023, using a discount rate of 10 percent. This is an indication of the costs required to roll out a particular scenario. Two of the scenarios result in appreciable savings (negative costs, or benefits) and lead to low NPVs, while three have relatively high costs. Benefits may accrue to the individual household through reduced energy costs. The first four scenarios reflect estimated penetration rates; those expected to be realistic in the absence of estimated targets in the Smokeless UB program and which can be achieved in the time period indicated. The 5th scenario uses data from the Smokeless UB program.

Results—emission reductions

The results in terms of average emission reductions[22] over the period 2010–23 are presented in table 7-3. When these data are discounted at the same rate and combined

[22] Straight average over the entire period

Table 7-1: Cost elements that play a role in the different scenarios

	public investments			individual investments		
	generation capacity	infra-structure	subsidies	Stoves	home improve-ments	energy savings
Scenario 1: startup emissions (backlighting)						+
Scenario 2: clean stoves			+	+		+
Scenario 3: SCC + clean stoves	+		+	+		
Scenario 4: electric heating	+	+	+	+		
Scenario 5: relocation into apartments	+	+	+		+	

Source: AMHIB study.

Table 7-2: Net present value of the costs and direct benefits

	NPV (10%)
	million $
Scenario 1a: backlighting	7.9
Scenario 1b: modifications	-13
Scenario 2: clean stoves	-19
Scenario 3: SCC + clean stoves	34
Scenario 4: electric heating	1,307
Scenario 5: relocation into apartments *) over a 9 year period starting 2015	4,094

Source: AMHIB study.

Table 7-3: Average and maximum emission reductions

	avg reduction over 15 yr period	
	Average (%)	Maximum (%)
Scenario 1a: backlighting	37	45
Scenario 1b: modifications	61	75
Scenario 2: clean stoves	57	80
Scenario 3: SCC + clean stoves	37	60
Scenario 4: electric heating	63	85
Scenario 5: relocation into apartments *) over a 9 year period starting 2015	31 *)	69

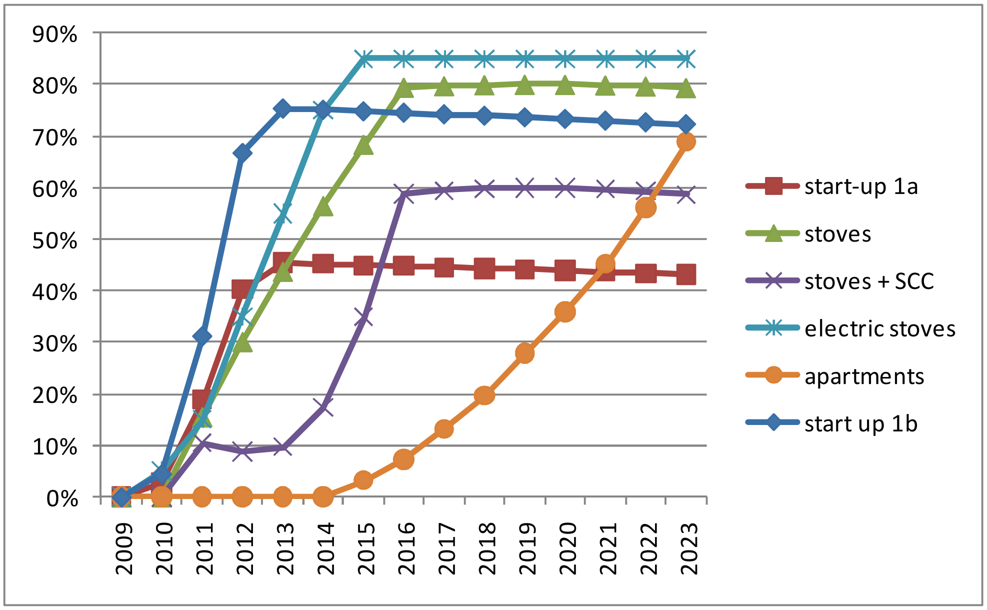
Source: AMHIB study.

with the costs for the scenario, an indicator is obtained for the effectiveness of the emission reduction scenario. Three of the scenarios have a very significant impact: modifying the stove and lighting technique (1b), introducing cleaner stoves (2) and electric heating (4) in ger areas. These numbers do not reflect the viability of the scenarios, but the potential impact on reducing emissions. The table simply reflects the "what if" situation—what would be the emission reduction if x percent of the households moved into apartment buildings; if y percent adopted electric heaters while continuing to live in their homes; or if z percent replaced its old coal stove for a new one, etc.

Figure 7-1 shows the emission reduction that would be obtained if the scenario were fully implemented, and table 7-3 illustrates average reductions over the 15-year period along with the maximum attainable. Relocation into apartments would have a higher contribution if it were not for the lead times needed for construction and relocation.

Three of the scenarios are expected to have a long-lasting impact on the emission levels as they would implement irreversible solutions. Reducing the start-up emissions will immediately produce pollution benefits (short-term); electric heaters will only have medium-term benefits, because first the generation and distribution infrastructure need to be increased to cater for the increased electricity demand; and moving into apartments will have long-term benefits only, because time is needed to raise the financing and construct the required number of buildings.

Figure 7-1: Estimated emission reduction from ger area interventions



Source: Authors' illustration.

Discussion

Two of the scenarios yield more direct benefits (i.e., savings) than the costs needed to roll out the scenario. Reduced start-up emissions and certified stoves are options from both an economic standpoint[23] as well as a beneficiary's perspective. The other three scenarios imply more costs than benefits and actually require significant levels of investment.

When assessing the costs in combination with the potential emissions reduction, a useful measurement is the NPV of the investments needed to reduce emissions by one percent compared to a baseline scenario. This allows for a direct comparison of the different options (see table 7-4). For example, an investment of $1.6 million would be needed to obtain a one percent reduction in emissions for the SCC scenario, $22 million to obtain a one percent reduction from enabling electric heating in ger areas, and $133 million for the same reduction from constructing new apartment buildings and associated infrastructure. However, the NPV of the investments needed to convince people to replace their stoves or change their habits for lighting the fire are negative. This means that the benefits exceed the costs.

There are significant differences between the scenarios, both in terms of investment and in terms of benefits, and a more detailed economic and technical analysis should be conducted to determine the right mix of short- and long-term solutions. While this report explores a number of options, many more remain.

When establishing priorities, this cost-benefit analysis should not be considered in isolation of other important factors, such as technical feasibility, security of supply (e.g. if a new fuel is proposed), ease of implementing the proposed measure (e.g. changing behaviors is challenging), affordability, social acceptance, and strength of governance. With this caveat, the results of these estimated cost benefit analyses reveal that some measures generate significant financial benefits to consumers (fuel savings) which compensate for the investment costs of the measures. Other measures require a much higher level of investment and may take longer to implement

[23] Not counting health benefits or other societal benefits

Table 7-4: Relative cost-effectiveness of the different options

	NPV (US$ million) of costs to reduce Air Pollution by 1%	Investment costs US$ million
Scenario 1a: backlighting	0.2	0.7
Scenario 1b: modifications	-0.2	2
Scenario 2: clean stoves	-0.3	7
Scenario 3: SCC + clean stoves	0.9	50
Scenario 4: electric heating	21	1,163
Scenario 5: relocation into apartments	133	4,152

Source: AMHIB study.

with fewer financial benefits for consumers, but reduce pollution by a significant amount. These investments are also different, ranging from one-off capital subsidies for stoves to recurrent subsidies for fuel or electricity consumption over several years to large infrastructure investments. The optimal strategy will differentiate between these differences and impacts to ensure that short-term measures are implemented, while larger investments have the right amount of time to be adequately prepared over the medium-term.

See Table F.1(Impact and costs of the different scenarios for PM emission reduction) in annex F.

HOB emissions reduction option and costs (Scenario 6)

Scenario 6 (medium-term). This option does not refer to households, but to public schools, hospitals, and other buildings in ger areas that use a heat-only boiler (HOB). HOBs are not connected to the UB district heating system. While the capacity of household stoves typically remains below 10 kW, an HOB can exceed 1 MW. Their coal consumption and emission levels are much higher than household stoves which typically use 20–24 kg of coal per day in January, compared to an HOB, which uses on average 4 t per day. However, although emissions from ger area households are one of the two completely dominating contributors to total PM emissions in the city (the other one being the CHPs), HOBs make only a small contribution to total PM emissions.

There are about 160 heat-only boilers in 89 boiler houses in the six central UB ger districts (Bayangol, Bayanzürkh, Chingeltei, Khan-Uul, Songinokhairkhan, and Sukhbaatar). A higher number of boilers in the three outlying UB districts are not connected to the district heating grid (Baganuur, Bagakhangai, and Nalaikh). HOBs in the six central districts contribute to air pollution in UB but not the others, as they are physically too distant from UB (Baganuur is over 150 km away).

Ownership of an HOB is partly public, partly private. Most privately owned HOBs are already technically efficient as many have been replaced previously. Some of the public HOBs are managed by private companies, and some public HOBs have already been replaced. In total, 40 percent of the HOBs in the 89 boilers houses do not need to be replaced, as they are efficient already. It must be noted that the actual efficiency of the HOBs depends on the operation and maintenance of the boilers. Recent technical assistance work supported by JICA reveals a high variability in technical skills and know-how among boiler operators. Thus, poor operation, even of newer boilers, could be a contributing factor to higher than expected source contributions from HOBs.

In the following scenario, all remaining inefficient HOBs are replaced—the medium efficient HOBs over a 3-year period and the most inefficient HOBs over a period of 8 years. Data from a 2009 market study of HOBs and coal-fired water heaters, 2009, CBDICFP (JICA

Table 7-5: HOB baseline data

baseline data	Installed 2010	Efficiency	Emission	Consumption t/d
Efficient HOB	36	80%	100%	400
Medium efficient HOB	18	60%	130%	600
Inefficient HOB	36	40%	160%	800
Total	90			

2009) have been used for unit consumption data and efficiency data. The Smokeless UB program gave cost data for the replacement of HOBs at $214/kW. This figure has been used, with some miscellaneous costs added, to give a total cost of replacement of $150,000 for an inefficient HOB and $125,000 for a medium-efficient HOB. All relative fuel savings and emission reductions have been calculated using the data in table 7-5.

See table A-2 (Results HOB Scenario) in the appendix to chapter 7.

Soil suspension reduction options and their costs

Scenarios 7 and 8 include two additional scenarios of fugitive dust reduction to address PM_{10} are included: (1) paving of unpaved roads with the construction of sidewalks and sweeping the newly paved roads and existing paved and unpaved roads; and (2) increasing vegetation in the city.

Scenario 7: Road dust reduction. In ger areas of UB (including the city center, mid-tier, and fringe ger areas), the combined length of earthen and paved roads is 80,929 km with the majority, 72,313 km or 89.4 percent, being earthen roads (Kamata et al 2010). It is anticipated that 500k m of these earthen roads will be paved and sidewalks constructed from 2016 to 2023. Also, it is assumed that these newly paved roads will be swept. In addition, it is also expected that existing paved and unpaved roads will be swept, with an annual increase of 1,000 km for each category of road. Data for capital costs for road pavement and for sidewalks were obtained from Kamata et al. (2010); emission factors for paved and unpaved roads were obtained from Guttikunda (2007). The costs for this scenario are mainly the costs of paving the road, constructing sidewalks, maintaining these roads and sidewalks, and sweeping.[24] Based on the above assumptions, PM_{10} reduction from roads are estimated from (a) newly paved roads and the sidewalk along the newly paved roads; (b) sweeping of these newly paved roads; and (c) sweeping of existing paved and unpaved roads. Only hard surfaced unpaved roads are supposed to be swept.

Washing or wet methods of cleaning the roads may further enhance the PM_{10} reduction, but are not included in the analysis due to the scarcity of water, dryness of the climate, and the freezing winters. It is assumed that the dustiest roads will be paved and swept first. Unpaved roads in the city center and areas nearby are assumed to have less traffic than paved roads but higher traffic than the average unpaved roads. It is also assumed that the feasibility study, environmental impact assessments and other safeguard issues, financial mobilization, and construction will be conducted during 2010–15.

Control techniques for fugitive dust sources generally involve watering, chemical stabilization, or reduction of surface wind speed with windbreaks or source enclosures. Watering, the most common and, generally, least expensive method except in water-scarce and dry areas like Mongolia, provides only temporary dust control. The use of chemicals to treat exposed surfaces provides longer dust suppression, but may be costly, have adverse effects on plant and animal life, or contaminate the treated material. Windbreaks and source enclosures are often impractical because of the size of fugitive dust sources. The reduction of source extent and

[24] An estimate of operation and maintenance cost is obtained from Bank transport staff. An estimate of sweeping cost is derived from a Bangkok Air Quality Management project report (World Bank 2007).

the incorporation of process modifications or adjusted work practices, both of which reduce the amount of dust generation, are preventive techniques for the control of fugitive dust emissions. These techniques could include, for example, the elimination of mud/dirt carryout on paved roads at construction sites. Conversely, mitigative measures entail the periodic removal of dust-producing material. Examples of mitigative measures include clean-up of spillage on paved or unpaved travel surfaces and clean-up of material spillage at conveyor transfer points.

For haul trucks, for example, there are several dust reduction practices. These include reducing haul truck speed and maintaining safe following distances, watering haul roads, treating haul roads, and maintaining equipment cabs. Reducing the haul truck speed is the simplest method. Implementing a policy to ensure that trucks do not follow within 20 seconds of another truck can result in a 41 to 52 percent reduction in airborne respirable dust exposure to the following truck.

The use of water on haul roads is the most common dust reduction method. Watering the haul road on the test section in a study allowed instantaneous dust concentrations to remain below 2 mg/m3 for over three hours. Past research has shown that watering haul roads with a water truck once an hour has a control efficiency of 40 percent for total suspended particulates (TSP). If watering is increased to once every half hour, the control efficiency for TSP increases to 55 percent. The control efficiency was defined as a comparison of the controlled (watered) emission rate to the uncontrolled emission rate. The EPA reported several test results of watering haul roads. The results ranged from a control efficiency of 74 percent for TSP for the three to four hours following the application of water at a rate of 2.08 L/m2 (0.46 gallons/yd2) to a control efficiency of 95 percent for TSP for 0.5 hours after the application of 0.59 L/m2 (0.13 gallons/yd2).

Treating haul roads generally involves the application of chemicals, and requires a significant amount of road maintenance. In one study, control efficiencies were 95 percent for magnesium chloride and 70 percent for a petroleum derivative for controlling haul-truck-generated dust.

Maintaining equipment cabs in good operating condition also reduces operator exposure to respirable dust. A study conducted on dozers and drills demonstrated that properly maintained cabs can attain dust reductions of 90 percent for drills and between 44 percent and 100 percent for dozers. The variations in the dust reductions for dozers were attributed to re-entrainment of internal cab dust. An additional study completed on haul trucks, which involved the retrofitting of a cab with a filtration/pressure air conditioning system to produce positive pressure in the cab, showed that properly maintained cabs are able to produce a potential 52 percent reduction of respirable dust (Reed and Organiscak 2007).

These measures are not included in the cost-benefit analysis of this work.

Scenario 8: Greening the city with vegetation. Suspension of dust from the soil surfaces will be reduced by a mix of simple vegetation, grass, bush and trees because it binds and covers the open soil and thus prevents suspension of dust to a considerable degree if the vegetation cover is successfully established. In addition, some of the dust already suspended, as well as a fraction of all particles in the air, will also be captured by the vegetation, although this is a minor effect compared to the reduction of the suspension. The number of areas to be vegetated and the costs of vegetation are derived from the smokefree Ulaanbaatar national program for 2010–16. In the program, 0.7 percent (about 952 hectares) of Ulaanbaatar's land is annually vegetated during the period and the program is expected to continue from 2011 to 2023. This vegetation includes different of types of vegetation (e.g., a mix of simple vegetation, grass, bushes, and trees), boundary marking, and protecting fences such as reforestation, planting broad-leafed trees upstream of the Tuul and Selbe rivers, greenbelt establishment, land reclamation, and so forth. The program mentions other initiatives including a ger area garden, a garden near power plant number four, national park, and dust reduction through re-vegetating city public space and roads—although it does not specify how many hectares will be vegetated. These actions are not included in the assumption of annual vegetation of 952 hectare. Due to UB's harsh

environment, it is expected that half of the annual increase in vegetation cover will die each year.

This scenario incurs the cost of planting and maintaining the vegetation. The Smoke Free Ulaanbaatar national program 2010–16 aims to plant vegetation across the city, not merely alongside the roads. Thus, the estimated PM reduction due to suspension prevention operates on the total soil dust suspension emissions of the whole city. The estimated reduction in PM_{10} due to the capture of already airborne particles by the vegetation operates mainly on particles from all low-level PM_{10} emissions in UB (see table 3-3). The PM reduction due to the vegetation's prevention of suspension, when successfully established, is estimated to be 80 percent. Local studies on this are not available, and results from studies carried out by Grantz et al. (1998) have been used (see annex F). PM_{10} deposition in air to different types of vegetation is very specific to each situation (e.g., wind speed, surrounding building, climate, temperature, latitude, type of vegetation, and so on). Local data on the PM_{10} deposition rate to trees or any types of vegetation is not available for UB. Thus, the estimate is very conservative and will change depending on the values used (Hewitt 2010). Since local data on suspension reduction by and deposition to vegetation is not available, the estimate of PM reduction by the establishment of vegetation is considered a very tentative analysis. It is, however, a potentially very important measure, since much of the PM_{10} problem in UB originates from soil suspension. Studies of dust reduction by vegetation in UB should be conducted.

See table F.3 (Paving Roads and Greening the City) in annex F.

Summary

Table 7-6 gives a summary of the different scenarios and their specific costs, benefits, and impacts. It shows that the impact of the scenarios has a wide range, from about 5,000 tons to almost 190,000 tons of PM reduced over a period of 15 years. The costs also vary widely— some scenarios have direct benefits (i.e., fuel savings are larger than the direct costs of rolling out the scenario) while some costs are reduced by several hundred thousand dollars per t.

This analysis is intended to compare the various options, mainly based on data included in the Smoke Free UB plan. A more rigorous analysis is required before any of the scenarios is put into action.

Table 7-6: Summary performance of the various options

	max PM10	NPV costs	reduction over 15 years		$ per t reduction
	t/yr	million US$	avg/yr	total (t)	
Scenario 1a: startup emissions (backlighting)	19,731	-53.0	39%	114,440	-463
Scenario 1b: startup emissions modified stoves)	19,731	-35.8	58%	171,660	-208
Scenario 2: clean stoves	19,731	-0.3	26%	76,572	-4
Scenario 3: SCC + clean stoves	19,731	36.7	22%	66,579	550
Scenario 4: electric heating	19,731	1,410	63%	187,445	7,523
Scenario 5: relocation into apartments	19,731	4,094	31%	91,135	44,925
Scenario 6: HOB	1,077	5,9	32%	5,193	1,128
Scenario 7: road dust	9,954	66.7	16.8%	23,394	2,852
Scenario 8: Greening	13,557	2.5	3.8%	7,132	351

Source: AMHIB study.

8. Health Benefits of the Air Pollution Management Scenarios

This chapter estimates the monetized health benefits of the abatement options outlined in chapter 7. It estimates the year-to-year benefit achievable in the period 2010–23, as well as the present value in 2010 of the benefit accruing over the full period. The largest benefit derives from ger electric heating ($1,803 million), from introducing certified stoves ($1,605 million), and from reducing start-up emissions using the lighting technique ($1,599 million). Other technical and nontechnical ger area interventions—such as relocating ger residents into apartments—also produce substantial health benefits. Reducing emissions from HOBs, road dust reduction, and greening scenarios give some health benefits, although they are small when compared to the other scenarios.

The previous chapter explored management scenarios for reducing emissions from ger stoves and HOBs in terms of their costs and potential emission reductions, as well as options for reducing road dust and windblown dust. The following chapter estimates the health benefits associated with the abatement scenarios year by year and calculates the present value of the benefit of each scenario. Finally, the health benefits accruing from the scenarios are compared with the costs of implementing the measures needed to realize the scenario.

A simplified approach based on the percentage reduction in emissions given in chapter 7 is used for each scenario, which also applies to the sources' contribution to total population-weighted exposure (PWE) in Ulaanbaatar. Therefore, for each year (2010–23) of a given scenario, the PWE (for PM_{10}) contribution for the relevant source category in table 3.3 above (for the base year) is multiplied by the percentage reduction in emissions as calculated in chapter 7. By this method, it is possible to estimate how much the total PWE in the city is reduced by the abatement measures. As any value of PWE corresponds to a certain health cost (which is the sum of mortality and morbidity costs, see chapter 6), the team is able to calculate the health benefit (i.e. the avoided health costs) associated with each scenario and each year of the scenarios. Only the base case method for calculating mortality impacts is applied in this chapter. To account for population growth, the resulting figures for health benefits with an annual growth rate of 5 percent are being adjusted. The annual average population growth rate in Ulaanbaatar in the period 1993–2008 was 4.3 percent, while the growth rate in the period 2000–08 was 4.7 percent. 5 percent is suggested as a reasonable estimate in the base case. Guttikunda (2007) assumes 5 percent, 8 percent, and 10 percent annual population growth toward 2020; the 10 percent figure is described as unlikely.

In addition to population growth and income growth, other welfare developments are likely to occur. This implies that estimates of future potential benefits of interventions should be adjusted. Approximately 85 percent of the benefit is related to either mortality impacts and chronic bronchitis, both valued using the value of statistical life (VSL). Therefore, the income elasticity rate of VSL to adjust the benefit estimates is used. Studies conducted largely in the United States suggest that the income elasticity of WTP for mortality risk reductions is less

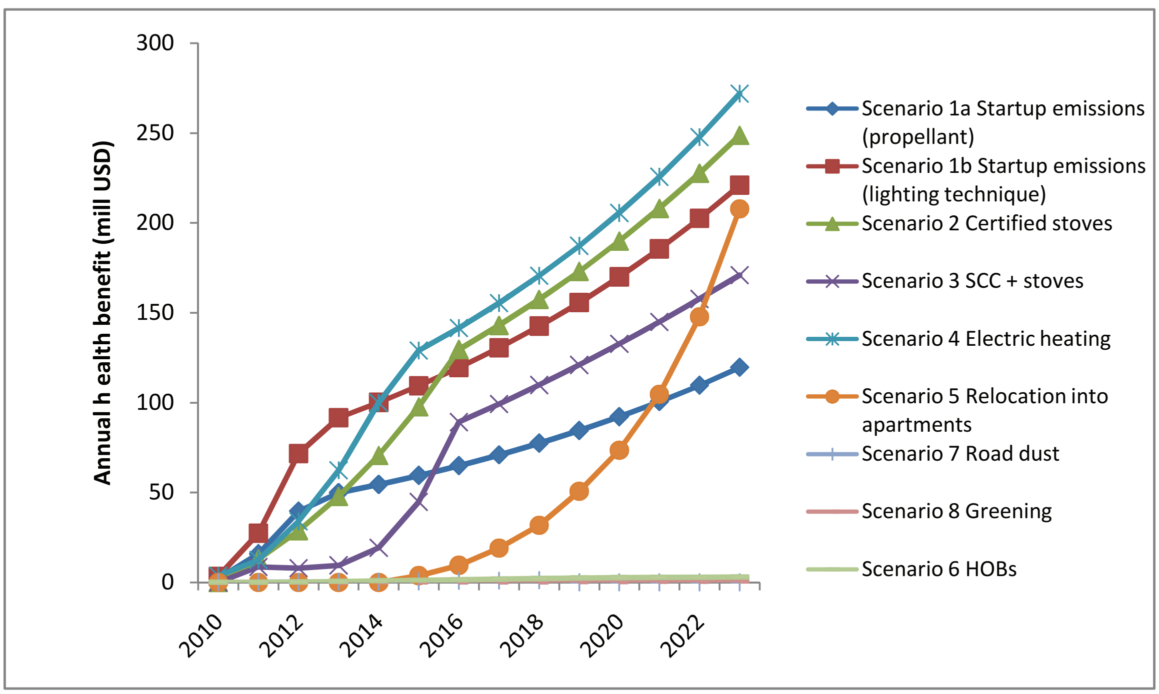
than one, with elasticities averaging between 0.4 and 0.6 (USEPA 1999). However, elasticities greater than 1.0 are suggested by research on the relationship between long-term economic growth and the VSL, by cross-country comparisons, and by new research that estimates the VSL by income quartile. Moreover, studies suggest that the elasticity varies by income level; that is, lower income levels are associated with higher income elasticities of VSL (Hammitt and Robinson 2011).[25] In Mongolia income levels are low, which suggests using an elasticity higher than 1.0. In the following calculations, an elasticity of 1.5 is used in the base case and 1.0 and 2.0 in the low and high case, based on the study by Hammitt and Robinson (2011)[25]. Assuming an economic growth rate of 10 percent, this means the benefit estimates are inflated with an annual growth factor of 15 percent. The discounted annual health benefit from Scenarios 1–8 are shown in figure 8-1.[26] Figures 8-2 and 8-3 show how the benefit estimates change when higher or lower annual population growth rates and income elasticities of VSL are being assumed. The health benefit to some extent mimics the emission reductions shown in figure 7-1 previously (especially in the low case), since the combined effect of assumed population growth and increased willingness to pay for risk reduction is partly canceled by the discount rate of 10 percent applied.

The value of the present health benefits for the various scenarios is presented in table 8-1.

[25] See Hammitt and Robinson (2011). In Ulaanbaatar we do not have to transfer VSL estimates from other, higher income countries, and thus are primarily interested in the time-series development of VSL versus income in the city. Hammitt and Robinson (2011) report elasticities in the range 1.5–3.0 in longitudinal studies. Since differences in longitudinal versus cross-section studies are yet not resolved, we choose to use an elasticity estimate based on the broader basis of studies covered by Hammitt and Robinson (2011) instead of the more limited evidence from longitudinal studies.

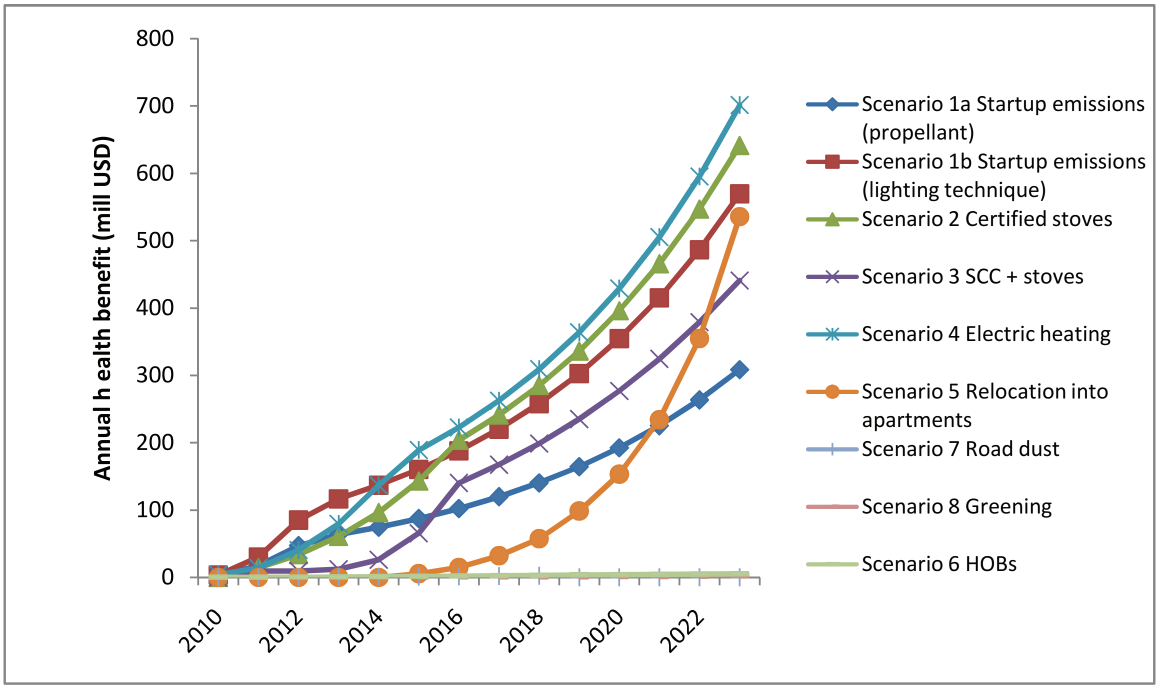
[26] The remaining 15 percent of total health benefits that are not valued using the VSL estimate are related to the direct cost of hospitalization. It is possible to argue that we should have used the economic growth rate of 10 percent to adjust hospitalization costs. This would however, have a minor impact on our results, and for simplicity we omit this adjustment.

Figure 8-1: Annual health benefit from abatement scenarios (mill USD) (discounted values), base case



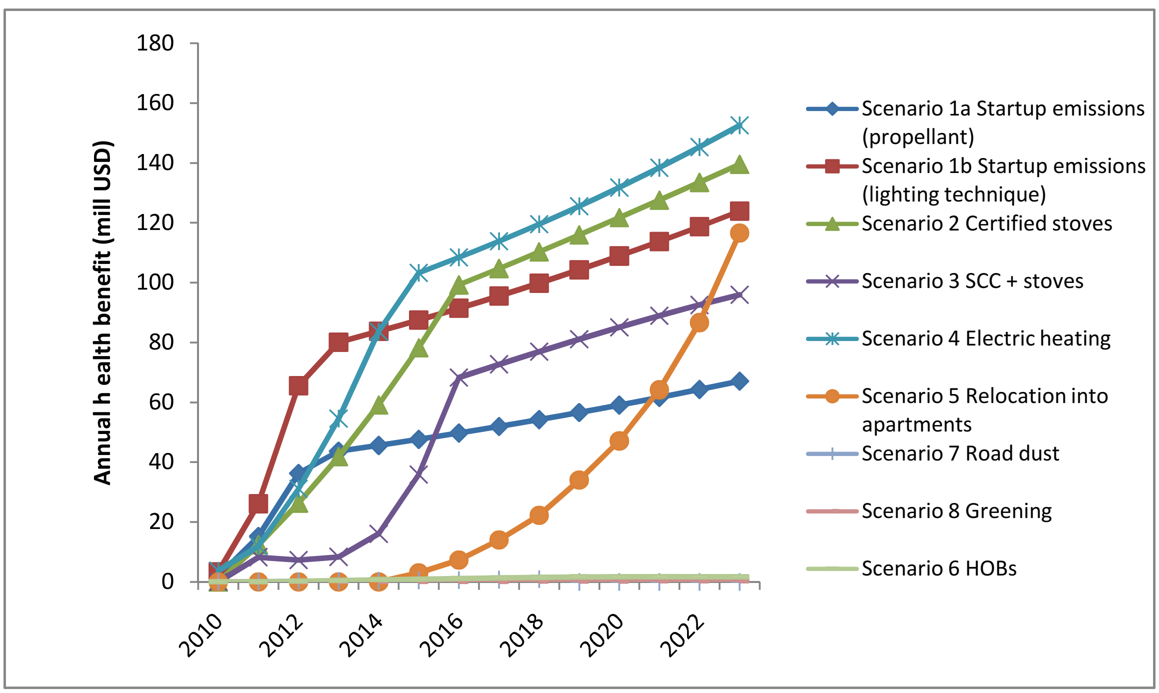
Source: Authors' illustration.

Figure 8-2: Annual health benefit from abatement scenarios (mill USD) (discounted values), high case assuming an annual population growth rate of 8% and an income elasticity of VSL of 2



Source: Authors' illustration.

Figure 8-3: Annual health benefit from abatement scenarios (mill USD) (discounted values), low case assuming an annual population growth rate of 5% and an income elasticity of VSL of 1



Source: Authors' illustration.

Table 8-1: Present value of health benefits ($ million), accumulated for the period 2010–23

	Present Value of health benefit ($ million)
Ger stoves:	
Scenario 1a: Reduce startup emissions (backlighting)	865.8
Scenario 1b: Reduce startup emissions (modified stoves)	1,599.0
Scenario 2 Certified stoves	1,605.0
Scenario 3 SCC + cleaner stoves	1,028.5
Scenario 4 Electric heating	1,802.9
Scenario 5 Relocation into apartments	597.1
HOB emission reduction:	
Scenario 6 HOBs	19.7
Road dust reduction:	
Scenario 7 Road dust	66.9
Windblown dust reduction:	
Scenario 8 Greening	58.1

Source: AMHIB study.

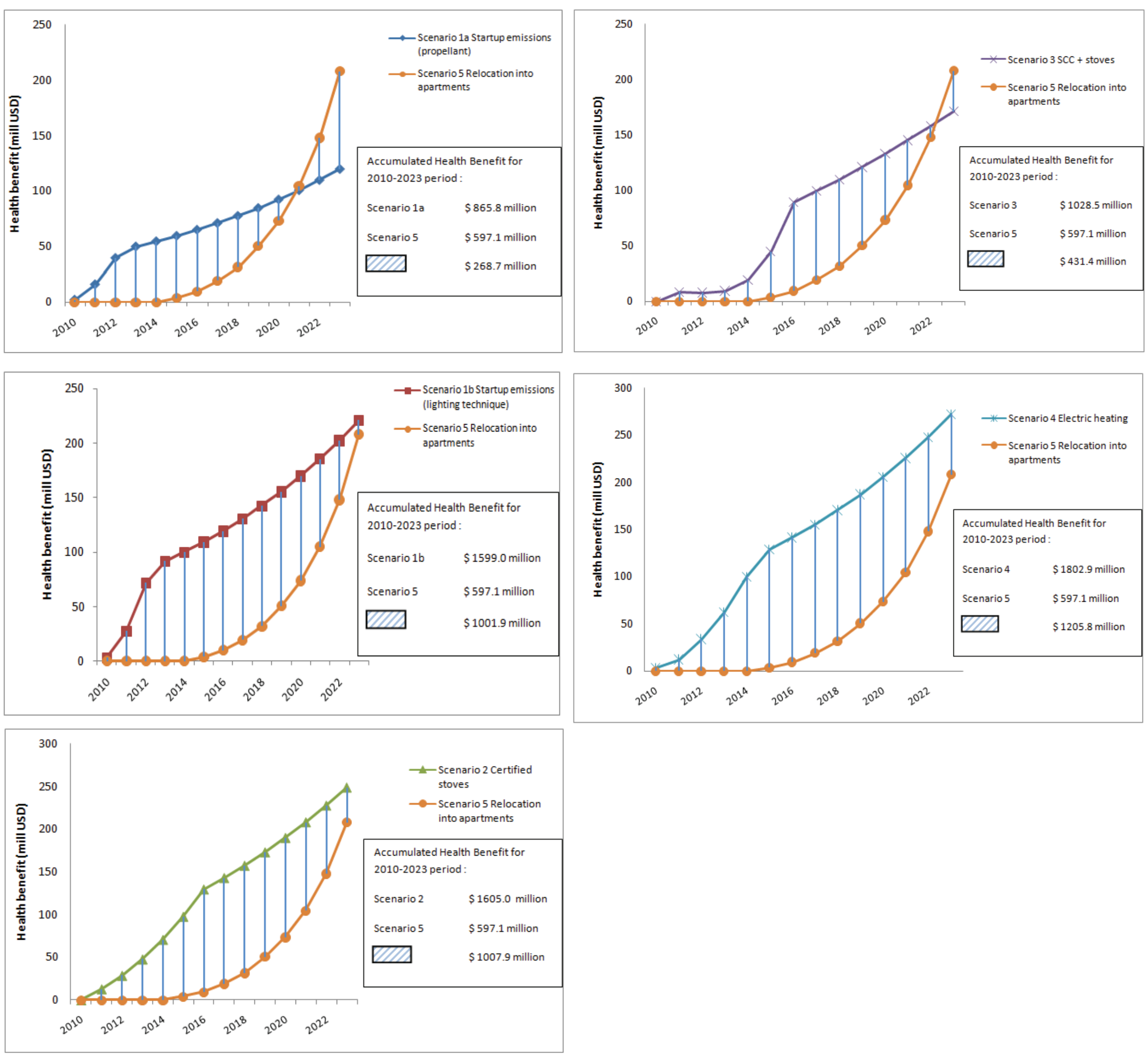
The largest benefit in terms of reduced health costs derive from ger electric heating (Scenario 4), estimated at $1,803 million; from introducing certified stoves (Scenario 2), estimated at $1,605 million; and from reducing start-up emissions using the lighting technique (Scenario 1b), estimated at $1,599 million. Reducing start-up emissions using propellant (Scenario 1a) entail somewhat lower health benefits, about $866 million. Replacing existing stoves and fuels with cleaner stoves and semi-coked coal (Scenario 3) and relocation into apartments (Scenario 5) entail a health benefit of, respectively, $1,029 million and $597 million. The HOB, road dust reduction and greening scenarios also give health benefits, although the benefits are small when compared to the other scenarios.

In chapter 9, the estimated health benefits are compared with the costs of implementing the scenarios.

As shown above, the different abatement scenarios being considered have quite different present values of health benefits. An alternative comparison between the scenarios is to compare the avoided costs between short-term measures to medium- and long-term measures. Medium– and long-term solutions require time to be prepared properly, with substantive investments that have to be mobilized over several years, but people continue to breathe unhealthy air, which results in an increase in both morbidity and mortality. A relevant estimation is therefore to assess the avoided costs of some scenarios when compared to other scenarios.

For example, a comparison of short-term (immediately available) interventions like application of certified stoves (scenario 2), application of new lighting techniques (scenario 1b) or propellant techniques (scenario 1a) to reduce startup emissions in the stoves compared with the long-term intervention of relocating inhabitants into new apartments, shows significant avoided costs. Figure 8-4 illustrates

Figure 8-4: Difference in health benefits ($ million) between five short to medium term measures and a long-term scenario (relocation into apartments).



Source: Authors' illustration.

the extent of avoided cost between the short- and long-term interventions.

Table 8-2 shows how much the avoided costs estimated in absolute mortality and morbidity (measured in cases of chronic bronchitis, and cases for respiratory and cardiovascular diseases) may be between the same short-term interventions and long-term interventions exemplified by relocation into apartments. This does not mean that there should be entirely focus on short-term interventions, but rather that short, medium and long term interventions should be sought in parallel.

Table 8-2: The difference in health benefits ($ million and absolute numbers) between five short to medium term measures and a long-term scenario (relocation into apartments)

Compared Scenarios	Health Benefit (mill $)	Premature Deaths*	Cases of Chronic Bronchitis	Cases of RSD (HA)	Cases of CVDs (HA)
(i) 1 a and 5	268.7	693	815	6,673	5,707
(ii) 1b and 5	1,001.9	2,138	2,759	17,741	15,434
(iii) 2 and 5	1,007.9	2,052	2,666	16,775	14,615
(iv) 3 and 5	431.4	908	1,130	8,036	6,940
(v) 4 and 5	1,205.8	2,456	3,226	19,580	17,102

* Applying WB 2007 dose response function. (World Bank 2007).
Source: AMHIB study.

9. Cost-Benefit Considerations

This chapter compares the annual health benefits to the annual implementation costs for each scenario as well as over the full implementation period. Benefits are calculated in terms of their present values (PV) and costs are calculated as net present values (NPV), since, as described above, there are some cases where energy savings reduce the costs. The PV and NPV of future annual costs and benefits represent the value in 2010 of costs and benefits accruing over the period 2010–23 and enable a cost-benefit evaluation of the different scenarios. The largest net benefit is calculated for reducing start-up emissions using the lighting technique ($1,635 million) and from introducing certified stoves ($1,605 million), while relocating ger area residents to apartments carries by far largest net cost (about $3,497 million).

The health benefit and the abatement costs are presented in the two left-most columns in table 9-1. Both benefits and implementation costs vary considerably between the scenarios. Cost-benefit considerations of benefits and abatement costs can be calculated in several ways. One way is to calculate the "net benefit" for each scenario. In table 9-1, the "net benefit" estimates are calculated by subtracting the net present value (NPV) of abatement costs from the present value (PV) benefit value for each scenario. Sensitivity calculations assuming higher or lower annual population growth rates and income elasticities of VSL are included in the table (see details regarding the choice of parameters in chapter 8).

The largest net benefit derives from scenario 1b (start-up emission reduction using improved lighting technique), while scenarios 1a, 2, 3, and 4 (start-up emission reduction/backlighting, certified stoves, improved stoves/semi-coked coal, and electric heating) also yield substantial net benefits. Improved HOBs produce a net benefit, but relatively smaller than that of the ger area interventions. The relocation of ger residents into apartments has the largest net cost—estimated to be more than $3 billion. While the health benefit of relocation is estimated to be substantial, it is the lowest among the ger area interventions. Scenario 4 (electric heating) is the option producing the largest health benefit, but the costs are also substantial, yielding the lowest net benefit among the ger area interventions.

The dust reduction scenarios (7 and 8) yield relatively low health benefits. Scenario 8 (greening) also has a low cost, resulting in a clearly positive net benefit. Reducing road dust (scenario 7) appears to be a rather expensive option, yielding a net cost around zero and having the highest cost/benefit ratio among the scenarios with a positive implementation cost.

Cost-benefit considerations for each of the scenarios

The scenarios are discussed in the order of intervention type, starting with the largest net benefit. Please refer to chapter 8 for a detailed description of the scenarios.

Table 9-1: Comparison of present value (PV) of health benefits (base case) with net present value (NVP) of implementing costs , and net benefit (PV minus NPV) for the eight abatement scenarios, 2010 (mill USD)

	Present Value of health benefit	NPV of costs of implementing the option	Net benefit	C/B-ratio
Ger stoves:				
Scenario 1a: startup emissions (backlighting)	865.8	-53	918.8	865.8
Scenario 1b Startup emissions (modified stoves)	1,599.0	-35.8	1,634.8	1,599.0
Scenario 2 Certified stoves	1,605.0	-0.3	1,605.3	1,605.0
Scenario 3 SCC + cleaner stoves	1,028.5	36.7	991.8	1,028.5
Scenario 4 Electric heating	1,802.9	1,410.0	392.9	1,802.9
Scenario 5 Relocation into apartments	597.1	4,094.0	-3,496.9	597.1
HOB emission reduction:				
Scenario 6 HOBs	19.7	5.9	13.8	19.7
Road dust reduction:				
Scenario 7 Road dust	66.9	66.7	0.2	66.9
Windblown dust				
reduction:				
Scenario 8 Greening	58.1	2.5	55.6	58.1

Note: Base case: Annual population growth: 5% and income elasticity of VSL: 1.5
Source: AMHIB study.

Scenario 1b: Reduce startup emissions (lighting technique). Net benefit: $1,635 million

Measurements confirm that PM emission reductions in excess of 80 percent can be obtained when the fire is started differently and when the fire is not allowed to die down but continues to burn throughout the day and night. This scenario uses a back-lighting method of starting the fire, in combination with a slight change in the design of the stove that can be realized by inserting more firebricks into the stove. This will reduce the size of the combustion chamber and result in a slower and cleaner burn. However, it should be noted that changing behavior, such as customary methods of lighting a traditional stove, may be challenging.

This represents a major health benefit from this scenario since it reduces the emissions from the ger stoves very significantly and is estimated to be above $1,599 million. It has a (small) negative cost, since fuel is saved by the lighting method (less use of wood).

Scenario 1a: Startup emissions (backlighting). Net benefit: $919 million

This is similar to scenario 1b, except that the fire starting method is different. It uses another fuel—such as LPG—than wood to start the fire. Simple LPG canisters can easily be used and are already available in ger areas.

For this scenario the health benefit is very large, estimated at close to $866 million, and also there are (small) negative costs, because fuel is saved.

Scenario 2: Certified stoves. Net benefit: $1,605 million

This scenario envisions replacing existing stoves with better coal stoves (“improved stoves”),

without changing the fuel. Measurements taken elsewhere than in UB are conclusive and show that the correct type of stove can obtain emission reductions of 50–80 percent. Similar measurements are currently being taken in UB. This scenario attempts to make cleaner stoves available to users on a large scale. This requires an awareness campaign to convince households of the usefulness of changing their stove, a financing mechanism with a possible subsidy component to enable households to purchase the stove and to promote a wide variety of eligible stoves to address customer preferences and increase chances of rapid market penetration. The scenario would also require an eligibility program to select the appropriate stoves for support and dissemination and create a sustainable production capacity of such stoves.

Estimated health benefits are about $1,605 million. The implementation cost is estimated to be near zero (costs and savings equal each other).

Scenario 3: Semi-coked coal (SCC) + new stoves. Net benefit: $992 million

This scenario looks to replace existing stoves and fuels. Semi-coked coal (SCC) receives significant attention, and while SCC can burn cleanly in an appropriate stove, there are two problems associated with this fuel. It remains difficult to light and the production costs are higher than raw coal. The scenario therefore includes setting up the production capacity of SCC, an awareness campaign to convince people to start using it in new stoves, and subsidies to enable the use of SCC at equal costs as raw coal.

The estimated health benefit is about $1,029 million for this scenario. There is a positive implementation cost of about $37 million, giving a net benefit value of about $992 million.

Scenario 4: Electric heating in Gers. Net benefit: $393 million

In this scenario people do not relocate but start using electric stoves for heating and cooking in their current homes. The cost of electric stoves and heaters, the cost of electricity minus the savings in heating fuel, and the cost of infrastructure for incremental generation and distribution capacity is incorporated into the cost analysis. The scenario assumes that most people in ger areas will actually switch to electricity once the government announces that this option is now available.

The health benefit value is the highest of all scenarios, almost $1,803 million, since emissions from ger homes are considered to be reduced to almost zero. There is, however, a large cost to implement this scenario, over $1,400 million. This includes the infrastructure development (power generation, lines, etc.). Thus the net benefit value is reduced to about $524 million, but it is still positive, meaning the health benefit is considerably higher than the cost.

Scenario 5: Relocation of ger population into apartments. Net benefit: $3,497 million

In this scenario, new apartment buildings are set up in newly developed areas, in existing ger areas, and in other cities. The impact is relatively simple, as coal consumption can be avoided almost completely (from heating in coal stoves) although there will be an increased contribution from the district heating system. The very high costs of construction, as well as the incremental capacity needed for district heating, is incorporated in the cost analysis.

Even if the emissions from the Gers are almost eliminated in this scenario, the health benefit, of almost $597 million is much less than for the electric stove scenario above, where ger stove emissions are also eliminated. This is because of the slow implementation of the relocation scenario, as the apartment buildings need to be built. In the meantime, ger residents are still exposed to emissions for many years, reducing the health benefit that can be obtained in the given period of time.

The costs are very high for this scenario, including apartment building construction, of approximately $4.1 billion. This gives a negative net benefit of about $3,497 million, meaning

that the costs are much higher than the estimated value of the health benefits.

Scenario 6: Improvement of heat-only boilers (HOBs). Net benefit: $14 million

In this scenario, all remaining inefficient HOBs are replaced, the medium-efficient HOBs over a 3-year period, and the most inefficient HOBs over a period of 8 years.

Both the health benefit and the costs of this scenario are relatively small. HOB emissions are not significant and have a slight impact on the population-weighted exposure (PWE), while improvement costs are also relatively small. There is a net benefit ratio of $14 million. As noted earlier, poor operation, even of newer boilers, could be a contributing factor to higher than expected source contributions from HOBs.

Scenario 7: Reduction of road dust suspension. Net benefit: $0

The scenario envisions the paving of roads to reduce fugitive dust. The costs include maintenance of the roads.

The estimated health benefit is $67 million, the same as the estimated costs. The net benefit thus is zero.

Scenario 8: Greening of urban areas to prevent dust suspension. Net benefit: $0.7 million

This scenario focuses on the greening of the city by planting vegetation (e.g., a mix of simple vegetation, grass, bushes, and trees), boundary marking, and protecting fences. It includes reforestation, planting broad-leafed trees upstream of the Tuul and Selbe rivers, greenbelt establishment, land reclamation, and so forth.

The estimated health benefit is $58 million. Given the relatively low cost of $2.5 million, the net benefit is $56 million.

Summary

Scenarios 1 through 5, which reduce ger area emissions substantially by various methods, yield substantial health benefits, and are all strong candidates for consideration, although some of these scenarios are substantially more costly.

Reducing the start-up emissions (Scenarios 1b and also 1a) and electric heating in the ger homes (Scenario 4) appear to produce by far the largest health benefits. Start-up emission reduction has a much lower net cost than installing electric heating, so scenario 1 provides by far the largest net benefit value.

Improved stoves and improved fuel (semi-coked coal) (Scenarios 3 and 4) also produce substantial health benefits at fairly low cost.

The HOB (Scenario 6) and the dust reduction (Scenarios 7 and 8) produce relatively small health benefits, at fairly low cost, according to the methodology used for the assessment. Dust from the extensive dry, uncovered surfaces in UB is difficult to suppress under the prevailing climatic conditions. The knowledge base regarding soil suspension and effects of abatement such as vegetation cover is weak. It seems worthwhile to look more closely at methods to establish vegetation cover on uncovered surfaces in UB and study its effect to reduce dust suspension, as this is such an important PM_{10} source.

As noted earlier, factors other than cost-benefit considerations are important in the process of selecting abatement scenarios, including technical feasibility, affordability, implementation capacity, and social acceptance and strength of governance.

Conclusions

This report presents the results of the implementation of a systematic approach by the AMHIB study to assess particulate air pollution in Ulaanbaatar and its effects. It evaluated costs and benefits of alternative abatement scenarios.

Socially acceptable and technically feasible emission and pollution exposure reduction targets are needed to guide the development of action plans. These targets are determined by the available technical options and the ability and willingness to pay for pollution reduction in the society. The costs of air pollution are paid through higher incidences of pollution-related illnesses, and mitigation costs are covered from people's pocketbooks and the budget of the communities. What and how to pay for air pollution and its reduction is a choice to be made by civil society and its representatives. Due to the complex nature of air pollution, an open discussion of options and their estimated impacts based on an analytical framework using best available data and analysis methodologies is recommended. Cost-benefit analysis and estimating avoided health costs of each policy option, together with other factors held important by Ulaanbaatar's citizens, should be considered in choosing clean air strategies. Setting targets that have been openly discussed helps build widespread support for pollution abatement activities that involve asking people to change environmentally damaging behaviors. Many in civil society, especially the poorest in UB, will be asked to change their behavior in some way to improve air quality. They should become active allies in the reduction of air pollution in UB.

When faced with choices between proposed abatement measures, policy makers need to consider which criteria should be used to prioritize measures. At the core of the local air pollution abatement program is its ability to reduce pollution and the harmful effects it has on the population. The selection criteria could be (a) the degree to which the abatement measure, or a package of measures, moves toward meeting Mongolian or international air quality standards across all of Ulaanbaatar; (b) the net benefits of abatement measures, or a package of measures, taking into account of the value of health benefits versus abatement costs; (c) technical feasibility of the measure; (d) affordability of the measure to the population and the government; (e) ease of implementation (how quickly can it have an impact? Is it complicated to prepare and/or implement?); (f) social acceptance (will it be accepted by society); and (g) strength of governance associated with the abatement measure.

Due to the spatial distribution of the population and UB's extremely high concentrations of pollution, short-term strategies to reduce air pollution as soon as possible could achieve large improvements in health for the population in a significant part of the city, even though all parts of the city might not meet air quality standards evenly.

Additionally, the high peaks observed in daily air pollution coincide with observed emission peaks from the ignition and re-loading phases of the burn cycle in ger stove heating. Because these peaks comprise a significant share of PM average concentrations in wintertime, it may be a sound strategy to focus on the ignition and reloading phase of the burn cycle in abatement design. Laboratory testing of emissions during typical burn cycles has confirmed this indication.

The present assessment of the air quality situation in Ulaanbaatar and of the effects of some selected abatement measures has been based upon a wide range of existing data, reports and information, as described in this report. The assessment followed the basic concept for carrying out air quality management work. This includes studying monitoring data for air pollutants and meteorology; carrying out emissions inventories and dispersion modelling; and calculating pollutant concentrations and their distribution spatially and temporally, and the contributions from the various main source categories. Such calculations were carried out for the current situation—the AMHIB project used the period June 2008–May 2009, the latest year with an extensive data base—as well as for the situation assuming that some selected abatement scenarios are implemented. Calculations also were made for the reduction in population-weighted exposure to PM for a number of abatement scenarios, and the corresponding benefits in terms of reduced health costs. There are uncertainties related to this comprehensive chain of analysis. Uncertainties are related both to the data used as input to the analysis, as well as to the analytical methods used which correspond to state-of-the-art methods used by the scientific community worldwide.

The use of two different methods to assess the contribution to the PM exposure from the various main source sectors, and the relatively good agreement of models with the PM measurements, lends credibility to the analytical results in terms of the population's exposure to PM, its spatial distribution, and the distribution of the contributions from the various sources. Compared to other similar assessments, an important strength of the current study is the health benefit assessment, where local studies of the link between air pollution and hospitalization rates and of the local population's willingness to pay for reducing mortality risks were carried out during the course of the study and the results applied in the analysis. Uncertainties have to some extent been quantified. Data quality has been improved since 2009 when the preliminary analysis for Ulaanbaatar was published as a discussion paper (World Bank 2009).

While the health and environmental authorities are to be commended for undertaking a significant effort in recording air pollution data, there is a great need for additional data to be collected. Analysis of additional years of pollution data, especially for $PM_{2.5}$ mass and its constituents, would help confirm the epidemiological findings presented in chapter 4, which are based on only one year of data. In other cities around the world, previous studies examining the effects of daily exposure to air pollution on major outcomes such as mortality and hospital admissions typically involve several years of pollution and health data. Additional data in UB would ensure that the current findings were not due to chance alone and would provide additional statistical power to detect an effect (i.e., find statistically significant impacts). Thus, additional data would reduce the uncertainty in the epidemiology studies of health effects of air pollution in UB. In addition, measurement of specific constituents (i.e., elemental carbon, organic carbon, nitrate, metals, etc.) would aid in conducting health studies on specific sources of particulate matter. Specifically, the empirical association of each source with a given health outcome could be discerned. With this information, the efficacy of reducing specific sources could be examined explicitly. Currently, the calculation of benefits of controlling particulate matter in UB must assume that the health impacts of each unit change in pollution concentration is similar for each source.

The response of the population of Ulaanbaatar to questions about their health and, ultimately, their expressed willingness to pay to lower these risks are not inconsistent with what members of the study team have seen in other countries. In all countries that have taken surveys of the type administered in Ulaanbaatar, including China and Japan, the public has evidenced a strong aversion to bearing mortality risks and is willing to pay a significant fraction of their income to reducing such risks. The estimates of WTP as a fraction of household income are high in Ulaanbaatar compared to China and most developed countries, but income underreporting may be a more serious problem in Ulaanbaatar, which would inflate this percentage. The Ulaanbaatar population does appear to have less of an understanding of risk than populations in other countries. But whether people who understand risk are included or excluded from the analysis does not have a significant effect on WTP.

Based upon available data and the results of the comprehensive analysis presented in the report, the following conclusions can be drawn:

- Ulaanbaatar is definitely one of the most polluted cities, and it might be the most polluted city in the world in terms of annual particulate matter concentrations. Arguably, its severity is driven by extreme wintertime PM concentrations (see chapter 3).
- The population of UB is exposed to high concentrations of PM from different sources and with different chemistry and size fractions. The findings of the health effects study conducted as part of AMHIB support conclusions that can be drawn from the health effects literature—that there is a significant public health burden related to exposure to air pollution in UB (see chapter 4).
- The people in Ulaanbaatar are, similar to people in other cities and countries, willing, when asked, to consider the value of reducing the risks associated with high air pollution. A WTP of 159,000 tugrug for a 5-in-10,000

annual contemporaneous mortality risk reduction is concluded from the study. This translates into a value of statistical life (VSL) of 319 million tugrug, or $221,000, based on the official exchange rate, or $493,000 based on a purchasing power parity (PPP) exchange rate (see chapter 5).

- The needed effort to reduce air pollution is considerable. A reduction of more than 80 percent of the emissions across all four main sources of air pollution (ger stoves, soil suspension, road traffic, heat-only boilers) would come close to reaching the Mongolian air quality standards in most of the UB city area, which are equivalent to the middle interim target set for developing countries by the WHO. To achieve WHO global guideline values, the emissions reductions would need to be about 95 percent (see chapter 6). A combination of measures is thus needed to be able to reach Mongolian air quality standards.
- The annual cost of health damage attributable to current levels of air pollution in terms of particulate matter is estimated to reach 18.8 percent of Ulaanbaatar's GDP in 2008, or $463 million. Using an alternative approach to health damage estimation, this amount could increase to 27.9 percent of Ulaanbaatar's GDP or $687 million. The maximum achievable benefit from the described interventions (80 percent reduction in three sectors: ger area emissions, soil suspension, HOB emissions) is estimated to equal 7 percent of GDP in Ulaanbaatar in 2008, or $174 million (see chapter 6).
- Different options for reducing emissions from the ger heating systems have been proposed, and their costs estimated. It is possible to reduce air pollution in the short term through a number of interventions, given here according to increasing costs. These are: improved stove lighting methods, modifying traditional stoves, or replacing traditional stoves with cleaner stoves. The investment costs are limited and will be more than compensated through a reduction of the fuel costs. Medium and long-term solutions—such as semi-coked coal in combination with SSC stoves, electric heating in the ger areas, or moving into apartment buildings—will also reduce air pollution by a large factor, but at much higher costs. The SCC and electric heating solutions will require extended subsidies to equalize heating costs (see chapter 7).
- Saved health costs are substantially larger than the costs of the abatement for several of the abatement scenarios analyzed. Of the eight scenarios for which cost-benefit calculations have been carried out, the five scenarios in which ger area emissions are substantially reduced produce very large health benefits in terms of avoided deaths, with the present value of health benefits reaching $597–$1,803 million aggregated over the implementation period (2010–23). The short-term solutions produce substantial and immediate health benefits that aggregate into very large benefit values over the 2010–23 period (see chapter 8).
- Five of these scenarios have a net benefit (saved health costs minus abatement costs) in the range of $393–$1,635 million. This means that air pollution management in Ulaanbaatar can be carried out with a substantial economic gain, when health costs are taken into account (see chapter 9).

It is recommended that policy makers set targets such as the following and open a discussion with civil society on the costs and benefits:

- Set targets that would reach Mongolian air quality standards for PM_{10} as soon as possible and $PM_{2.5}$ targets by 2020.
- To achieve these targets, all main PM sources in Ulaanbaatar need to be addressed. Reductions are needed primarily in the emissions from ger heating systems. Dust suspension from uncovered soil surfaces, roads, and near-road surfaces are the second most important PM_{10} source in UB. Its control is difficult, but should nevertheless be pursued. Emissions reductions from the sources with less contribution to the population's exposure will also contribute to improved air quality. These sources include HOBs, exhaust PM from road traffic, and CHP emissions. For CHPs, the obvious intervention is to improve the operation of PM cleaning systems. The actual composition

of the abatement scenario mix should be guided by the cost-benefit considerations for the various options, as well as technical, implementation and financial feasibility.

- Recognizing socioeconomic constraints in Ulaanbaatar, it is further recommended that interim targets and reduction time lines be set for PM pollution reduction. If the population exposure to PM could be reduced by 50 percent in a relatively short term, health costs of $86 million would be saved annually. To achieve this, it is recommended to target the ger areas immediately, where pollution reduction benefits are greatest.
- Consider further the issue of soil suspension problem by better assessing the effect of establishing vegetation cover, maintaining road/sidewalk/gutter surfaces, cleaning the roads and preventing dust from entering road surfaces.
- Install continuous emission monitoring systems in power plants to ensure better operation of the flue gas cleaning systems.
- Begin an open and candid discussion of actual costs and benefits of abatement measures by (a) ensuring the abatement measures are *technically* feasible and their emissions reduction benefits are justified with sufficient evidence; and (b) appraising the full costs of abatement measures and their contribution to overall improvements in ambient PM concentration reductions, so they can be compared to the health cost reductions.
- Strengthen air quality monitoring and emissions inventories by providing sufficient operating budgets to key Mongolian air quality institutions.
- Establish state-of-the-art pollution monitoring stations within the ger areas as soon as possible.

The following is a summary of next steps following the completion of this AMHIB study based on the basic steps in the Air Quality Management (AQM) process introduced in this report. These recommendations are intended to improve the knowledge and analysis of the air pollution situation in Ulaanbaatar, and the effects on improved health that should result from the abatement actions:

Air Quality Assessment

- Air pollution monitoring: Monitoring with the use of state-of-the-art monitors within ger areas should include at least $PM_{2.5}$ and PM_{10}, SO_2, NO_X, and NO_2. In this development, the suggestions presented by the AMHIB team should be considered (see annex A).
- Inventory of emissions: There remains a need to improve the existing emissions inventory including emission factors (EF) for the various sources, especially ger stoves; fueling practices (e.g. number and timing of fire starts); total amount of fuel burned per source category; traffic data on main roads; and study of the soil suspension source. Population: the spatial distribution of the population as used for this report should be confirmed, and the population growth and its spatial distribution should be followed.

Environmental Damage Assessment

- Studies of the health status of the population should continue.
- Indications of the improved health status following abatement implementation should be studied.
- The population exposure assessment should be extended to take into consideration indoor air quality in ger areas.

Abatement Options Assessment

- Several technical assessments have been carried out recently. Studies of the performance of various ger stove designs, for various fuels, should be completed. Large-scale demonstration projects need to be rolled out immediately to test proposed concepts, especially in ger areas where the success of abatement measures depends not only on technical effectiveness but also on socioeconomic and strong cultural considerations. It is important to systematically progress from demonstration projects to scale up as quickly as possible, but only when concepts show promising impacts.
- As outlined in chapters 7–9 of this report, some measures can be implemented over 1–2

years while others will take several years to implement. Others may require feasibility study analyses reflecting the size of the proposed investment and technical complexity.

Cost-Benefit Analysis or Cost Effectiveness Analysis

- Cost-benefit analyses linking measures with results should continue to be updated.

Abatement Measures Selection

- Continued work should help to provide needed information to the government to develop and select abatement measures.
- Strike an optimal balance between short, medium, and long-term abatement measures.

Optimal Control Strategy

- Continue to set timetables and secure financing.
- Establish a monitoring and evaluation system that continually reports on air quality improvements and assesses impacts of abatement measures.
- Indications of improved health status following abatement implementation should be studied.

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Introduction to Attached CD-ROM

Annex A: Baseline PM Concentrations/Baseline in Ulaanbaatar June 2008 – May 2009

The purpose of this annex is to present the measurements of particulate matter (PM_{10} and $PM_{2.5}$) that was carried out under the AMHIB study during the period June 2008–May 2009. There were 8 monitoring stations in operation under the AMHIB umbrella during the entire period, although some shorter periods were not covered at some stations due to instrument non-availability or operational problems. In addition, 4 German donor stations (called GIZ stations) were in operation starting in November/December 2008.

The results of the measurements provide a basis for assessing the ranges of concentrations of PM_{10} and $PM_{2.5}$ that were experienced in UB during the AMHIB measurement period, separately for Ger and non-Ger areas.

The instrumentation for PM measurements at the AMHIB stations was based on what was available in UB in 2008, owned and operated by various institutions with mandate for and research interest in air pollution monitoring. As a result of this, the stations were equipped with instruments of different types and measurement principles. Financial and time constraints prevented the complete set up of a state-of-the-art monitoring network with uniform instrumentation. Preparations for the monitoring program revealed that the various instruments gave differing results, which was due to sampling and measurement artifacts of the various instruments. In order to provide a basis for comparable and as correct as possible results from the different stations, instrument inter-comparison campaigns were carried out during 4 different weekly periods during the year. The inter-comparison results could be used to develop data correction procedures to arrive at a common basis for the data from most of the stations.

Still, these instrument problems cause uncertainty in the PM monitoring results. Due to the resulting uncertainty, it is judged to be the correct procedure to present first in this Annex the data as they were measured, without corrections. Then, after applying the correction procedure, the corrected data are presented and the PM concentration levels in UB under the AMHIB period is assessed. The uncertainty caused by the instrument issue has been estimated. It is judged that the quality of the assessment of the PM concentrations in UB is acceptable, and gives an adequate basis for assessing the health effects of the PM concentrations as well as to support the analysis of the effects of abatement measures.

The corrected results provide a basis for comparison between measured and modeled concentrations using air pollution dispersion models. The air pollution modeling efforts presented in Annex C provide a more complete picture of the spatial variations of the PM concentrations in the UB area, and a more complete basis for the assessment of health effects and effects of abatement measures.

The annex also contains recommendations regarding continuing air quality monitoring in UB.

Annex B: Identification and Apportionment of PM Pollution Sources by Receptor Modeling

The purpose of Annex B is to present the results of the source apportionment analysis that has been carried out based upon PM data from the three AMHIB stations 2 (NRC), 3 (Zuun ail) and 6 (3 Khoroolol). The Nuclear Research Centre (NRC) of the National University of Mongolia (NUM) has been participating in an international project during many years, where particulate matter samples have been taken at the NRC station and been subjected to multielemental analysis at the Institute of Geological and Nuclear Sciences (GNS) in New Zealand. Receptor modeling has also been carried out on the data, lately using the PMF methodology (see below). Under the AMHIB project, this activity was enhanced such that PM samples suitable for receptor modeling were taken also at the AMHIB stations 3 and 6.

The annex presents the methodology and the detailed results of the source apportionment (SA) for each of the PM size fractions sampled at the stations (fine PM fraction - $PM_{2.5}$, coarse PM fraction - $PM_{2.5\text{-}10}$, and the sum of fine and coarse - PM_{10}).

The results provide a separate basis for assessing source contributions to PM in Ulaanbaatar. They can also be studied together with results of source contributions that can be extracted from the air pollution dispersion modeling work that has been carried out for Ulaanbaatar as a part of the AMHIB project, based upon an inventory of PM emissions from the sources in Ulaanbaatar and upon meteorological data. Annex C describes the dispersion modeling work and the comparison with the SA results from the receptor modeling described here in this Annex.

Annex C: Air Pollution Dispersion Modeling for Ulaanbaatar and Assessment of Source Contributions

The purpose of Annex C is to present the basis for the dispersion model calculations, the models, and the results. The dispersion models were used also in the preliminary assessment of concentrations and contributions from sources that was presented in the Discussion Paper (World Bank, 2009). New data has become available, and as a result of that the emissions inventory (EI) had to be updated. The Annex gives details on the updating of the EI. Through the measurements carried out by the AMHIB study (see Annex A), there is now a better basis for evaluating the model calculations, and this is presented in the Annex. The Annex also compares the results regarding source contributions to PM that come from the two methodologies: the statistical source apportionment based upon the elemental analysis of PM samples (described in Annex B) and the dispersion modeling described in this Annex, and develops conclusions on this issue.

The dispersion model calculations provide the spatial distribution of the PM concentrations across the 30x30 km^2 grid used, on an hourly basis. When validated by the measurements, this spatial distribution provides the basis for the calculation of the exposure of the population to PM pollution, e.g. in terms of the population averaged exposure. The methods and results of this calculation is presented. This population exposure figure is the input to the estimation of the health effects of the PM pollution in UB.

Annex D: Estimating the Effects of Air Pollution on Mortality and Hospitalization in Ulaanbaatar

In this annex, the results of the analysis of the association between air pollution and both mortality and morbidity in UB are presented. Similar epidemiological studies, conducted over the last decade on five different continents, have demonstrated associations between short-term (i.e., daily) changes in air pollution and premature death. Many other adverse health outcomes from daily, multi-day, or long-term changes in ambient air pollutants, including PM, have been reported.

PM is a mixture of liquid and solid particles of different chemical constituents and sizes. PM is typically designated as either PM_{10} or $PM_{2.5}$ (particles less than 10 or 2.5 microns in diameter, respectively) or as the difference between PM_{10} and $PM_{2.5}$ (known as ”coarse particles” or CP). $PM_{2.5}$ (known as ”fine particles”) is generated from many sources, including fuel combustion by mobile sources (cars, trucks and buses), stationary sources

(power plants and industrial boilers), and residential sources (home heating and cooking). CP can also be generated by mechanical grinding during industrial processing, by construction debris, and by natural sources such as sea salt and blowing dust. Fine particles are often thought to be more toxic on a weight-adjusted basis than coarse particles, since they are more likely to penetrate deeply into the lung. However, the evidence is somewhat mixed and may depend on the concentrations and the patterns of exposure and population characteristics. The various particulate matter metrics – including PM_{10}, $PM_{2.5}$, black smoke, and sulfates – appear to show fairly consistent associations with both premature mortality and morbidity. The latter includes outcomes such as hospital admissions, emergency room visits, heart attacks, asthma exacerbation, respiratory symptoms, work and school loss, and reduction in lung function.

Similarly, associations in epidemiologic studies have been observed between NO_2 and both mortality and morbidity. The primary sources for NO_2 are fuel combustion by mobile sources, and combustion of fossil fuels by power plants, factories, and residences. The epidemiologic studies indicating effects of PM and NO_2 are also supported by findings from toxicological and clinical studies.

Because of data limitations, most studies to date have examined the effects of relatively short-term exposure. Specifically, time-series or case crossover studies examine the correlation of daily changes in air pollution, typically over several years, with daily changes in mortality. These studies control for other potential confounding factors that vary over time and may be associated with mortality, so that an independent effect of pollution can be quantified. With increasing statistical sophistication, these studies have shown that either one-day or multi-day PM average concentrations are associated with both total mortality and cardiopulmonary mortality. Among the first of the multi-city studies on mortality, Schwartz et al. (1996) examined data from the Harvard Six Cities study. This database included monitors sited specifically to support ongoing epidemiological studies and to be representative of local population exposures. Consistent associations were reported between daily mortality and daily exposures to both PM_{10} and $PM_{2.5}$, with a 0.8% (95% confidence interval (CI) = 0.5, 1.1) increase in daily total mortality per every 10 μg/m³ change in PM10.

Since this effort, several other multi-city studies have been published for both PM_{10} and $PM_{2.5}$. For example, in a study of 10 USA cities, Schwartz (2000) examined the daily effects of PM_{10} and reported that a 10 μg/m³ change in PM10 (measured as a two-day average of lag 0 and lag 1) was associated with a 0.7% increase in all-cause, daily mortality. In another multi-city study, Burnett et al. (2000) analyzed total mortality data for 1986–1996 from the eight largest Canadian cities and found that both PM_{10} and $PM_{2.5}$ were associated with daily mortality. For PM_{10}, a 10 μg/m³ increase was associated with a 0.7% (CI = 0.2, 1.2) increase in daily mortality. Another study involving 29 European cities reported an association between daily mortality and PM10, with an overall effect estimated at 0.6% per 10 μg/m³ (Katsouyanni et al., 2001). Dominici et al., (2002) analyzed the 88 largest cities in the USA (NMMAPS) and found an association of about 0.27% per 10 μg/m³ of PM_{10}. Meta-analyses of earlier mortality studies suggest that, after converting the alternative measures of particulate matter used in the original studies to an equivalent PM_{10} concentration, the effects on mortality are fairly consistent. A recent meta-analysis of European studies suggested a mean increase of the risk of 0.6% per 10 μg/m³ PM10 (WHO, 2004). In addition, a meta-analysis of Asian studies indicated a mean increase of the risk of 0.4% to 0.5% per 10 μg/m³ PM_{10} (Wong et al. 2008).

More recently, data on $PM_{2.5}$ have become available to support analyses of effects on health. For example, Ostro et al. (2006) analyzed nine large counties in California and reported an effect of 0.6% increase in mortality (CI = 0.2, 1.0) per 10 μg/m³ $PM_{2.5}$. Fine particles were also associated with cardiovascular and respiratory mortality, as well with all-cause deaths for those above age 65. In a study of 25 U.S. cities, Franklin et al. (2007) found an effect of 1.2% (CI =0.3, 2.1) for a similar change in $PM_{2.5}$. Finally, in a study of 112 (for $PM_{2.5}$) and 47 (for PM_{10}) U.S. cities, Zanobetti et al. (2009) reported effects of 1% (CI = 0.8, 1.2) and 0.5% (CI = 0.2, 0.7) for 10 μg/m³ changes in fine and coarse particles, respectively.

It is important to note that much larger effects have been detected from the few studies that have examined long-term exposures to PM on cohort survival. In this type of study, a sample of individuals are selected and followed over time. For example, Dockery et al. (1993) followed approximately 8,000 individuals in six cities in the eastern USA over a 15-year period (the Harvard Six Cities study); and Pope et al. (1995) followed mortality rates over a 7-year period in approximately 550,000 individuals in 151 cities in the USA. These studies used individual-level data so that other factors that affect mortality could be characterized and adjusted for in the analysis. Once the effects of individual-level factors were determined, the models examined whether longer-term citywide averages in PM (measured as PM_{10}, $PM_{2.5}$ or sulfates) were associated with different risks of mortality and life expectancies. The estimated mortality effects of long-term exposure to fine particles (approximately 7 to 13% per 10 µg/m^3 of $PM_{2.5}$) are much larger than those associated with daily exposure. Importantly, these study results imply large differences in life expectancy. Specifically, 24 µg/m^3 difference in $PM_{2.5}$ between the cleanest and dirtiest cities is associated with an almost 1.5-year difference in life expectancy for the city populations (Pope, 2000). The difference for people who actually died from diseases associated with air pollution was estimated to be about 10 years. This is because air pollution-related deaths make up only a small fraction of the total deaths in a city. Since these earlier studies were published, several additional and supportive studies, involving other cohorts, have been completed (Eftim et al., 2008; Puett et al., 2008; Miller et al., 2007; Ostro et al., 2010). A comprehensive review of the existing studies and a discussion of the underlying biological mechanisms that underlie these effects are provided by Brook et al. (2010).

Annex E: The Willingness to Pay for Mortality Risk Reductions in Ulaanbaatar, Mongolia

This annex reports results from a stated preference survey designed to estimate the willingness to pay for mortality risk reductions in Ulaanbaatar, Mongolia. The survey includes both contemporaneous and latent risk reductions of a magnitude typically achievable through clean air policy. The study looks at mortality risk reductions of the magnitude and types typically resulting from air pollution control policy. While the prime objective with the study is to estimate the willingness to pay for mortality risk reductions in Ulaanbaatar in order to support the work in the AMHIB project, an additional intention is to build a more solid bridge for benefits transfer between developed and developing countries. The survey was conducted in winter 2010. Estimates of willingness to pay passed external and internal scope tests. Study results imply a value of statistical life of $221,000 (319 million tugrug) for contemporaneous 5 in 10,000 annual risk reduction using the official exchange rate to convert tugrug to U.S. dollars.

Annex F: Air Pollution Abatement Options and Their Costs in Ulaanbaatar

As several abatement options applied in chapters 7 to 9 involve various forms of stove improvement and replacement alternatives, this annex first presents some information about the emissions from stoves. Then the underlying data that has been applied to estimate the performance for each option as outlined in chapter 7 (startup emissions (backlighting, clean stoves, Semi-cocked coal plus clean stoves, electric heating, relocation into apartments, HOBs, road dust and greening) and references to the applied data are presented. Finally, the costs, savings and PM reduction for the different scenarios are presented for each year in the 15 years projected period.

Annex G: Data Annex

Section 1 of Annex G shows results of inter-comparison campaigns between instruments participating in the AMHIB measurement network. Section 2 presents the data correction procedures resulting from the inter-comparisons.

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