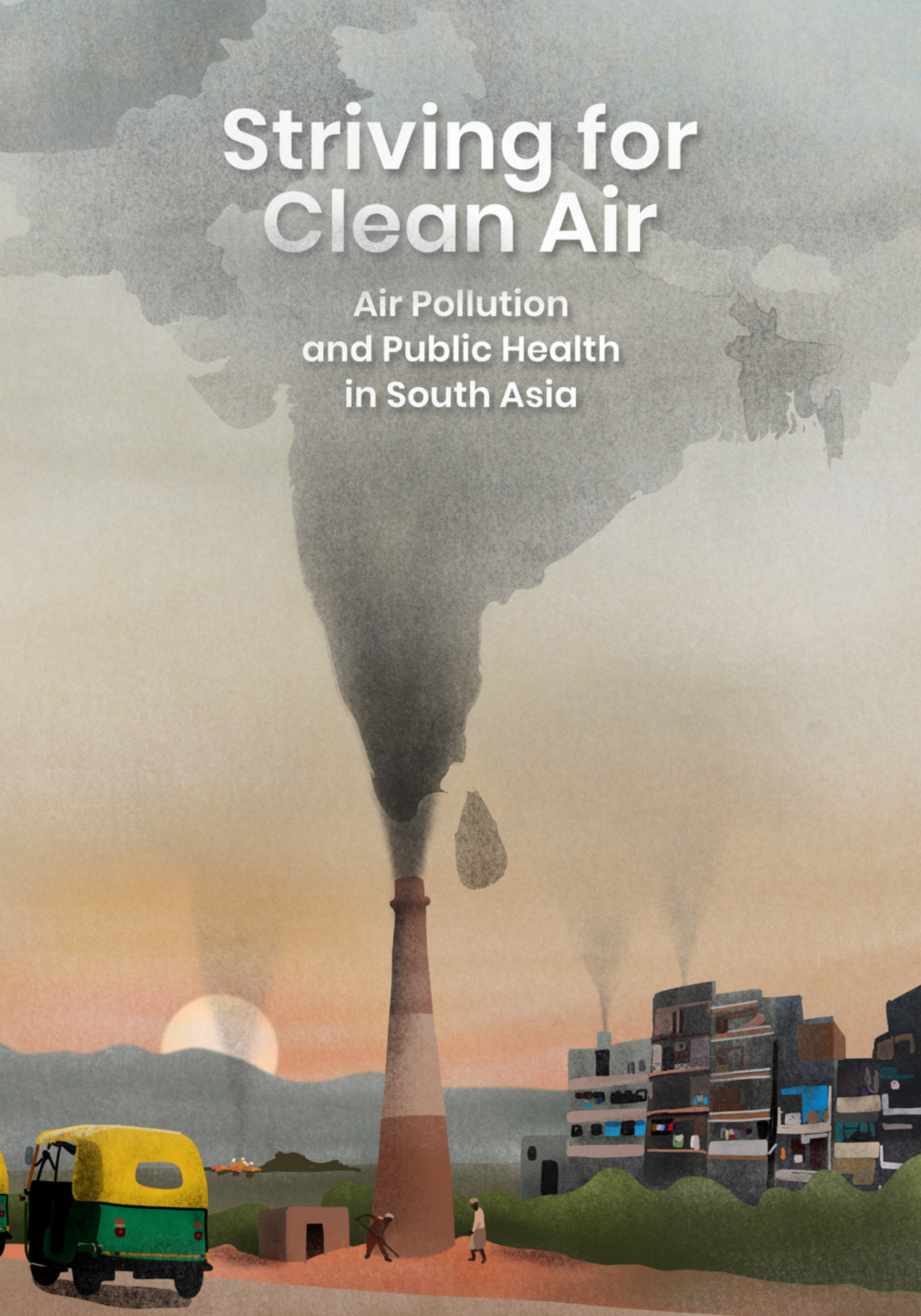
Striving for Clean Air

Air Pollution and Public Health in South Asia



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Cover and illustration designs: Reyes Work

Acknowledgements

This report was prepared by a team led by Muthukumara Mani under the guidance of Hans Timmer (Chief Economist) and Martin Raiser (Vice President) of the South Asia Region of the World Bank. The core team members include Jostein Nygard, Aiga Stokenberga, Michael Toman, Nadia Sharmin, Margaret Triyana, Siddharth Sharma, Martin Heger, Adanna Chukwuma, Michael Norton, Md. Shamemmur Rahman, Isabel Maria Ramos Tellez, Zara Ali, Utkarsh Saxena, and Ahmad Imran Aslam. The team was supported in the modeling work by a team from the International Institute for Applied System Analyses (IIASA) that included Markus Amann and Wolfgang Schöpp (former staff), and Gregor Kiesewetter, Pallav Purohit, Fabian Wagner, Chris Heyes, Adriana Gomez-Sanabria, Zbigniew Klimont, Parul Srivastava, and Jens Borken-Kleefeld. Additional support was provided by Maureen Cropper, Yongjoon Park and Bjorn Larsen.

The team greatly benefited from insightful comments and guidance from internal peer reviewers—Ernesto Sanchez-Triana, Carter Brandon, and Yewande Aramide Awe. The team is also grateful to other colleagues from the World Bank for their thoughtful comments and suggestions at various stages, most notably, Urvashi Narain, Magda Lovei, Christophe Crepin, Cecile Fruman, Lynne Sherburne-Benz, André Zuber, Nicholas Muller, Elena Karaban, Janet Minatelli, Pawan Bali, Yinan Zhang and Zoe Leiyu Xie.

The team thanks Elena Karaban, Mehreen Arshad Sheikh, Adnan Javaid Siddiqi and Diana Ya-Wai Chung for guidance and support on the communication and dissemination strategy. Rana Al-Gazzaz provided critical support to the production, communication and dissemination of this report. William Shaw provided editorial guidance. Peter Milne and Bart Ullstein provided excellent editorial support. The team also thanks Neelam Chowdhry and Ahmad Khalid Afridi for administrative support.

The team gratefully acknowledges timely financial support from the PARCC Trust Fund, a regional Trust Fund financed by the UK FCDO on regional cooperation on climate change. The team would like to thank participants of various regional as well national workshops and consultative meetings.

In producing this report, the World Bank emphasizes that air pollution initiatives and projects shall respect the sovereignty of the countries involved, and notes that findings and conclusions in the report may not reflect the views of individual countries or their acceptance.

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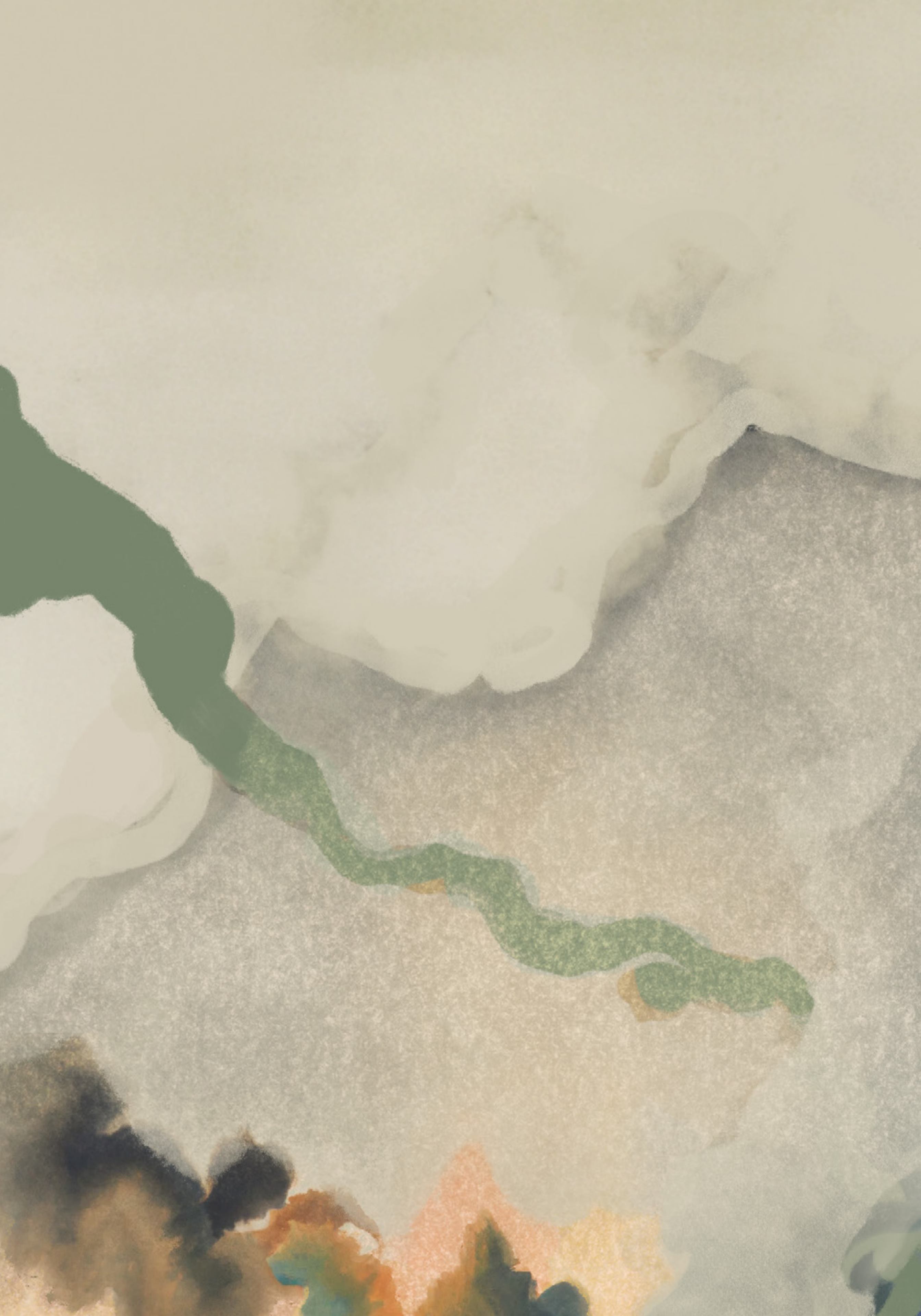
Abbreviations

Abbreviation	Name
AAP	Ambient Air Pollution
APHEA	Air Pollution and Health: A European Approach
AQCR	Air Quality Region
AQM	Air Quality Management
AQMD	Air Quality Management District
BC	Black Carbon
CAA	Clean Air Act
CARB	California Air Resources Board
CCDR	Climate Change Development Reports
CH_4	Methane
CIAM	Centre for Integrated Assessment Modelling
CLRTAP	Convention on Long-Range Transboundary Air Pollution
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
COI	Cost-of-Illness
CRAES	Chinese Academy of Environmental Sciences
EMEP	European Monitoring and Evaluation Programme
EPA	Environmental Protection Agency
ETS	Emissions Trading Systems
EU	European Union
FBC	Fluidized Bed Combustion
FIP	Federal Implementation Plan
GAINS	Greenhouse Gas and Air Pollution Interactions and Synergies
GDP	Gross Domestic Product
GHG	Greenhouse Gas
HAP	Household Air Pollution
IGP	Indo-Gangetic Plain
IHME	Institute for Health Metrics and Evaluation
IIASA	International Institute for Applied Systems Analysis
IV	Instrumental Variable
IQ	Intelligence Quotient
LPG	Liquefied Petroleum Gas
MEIC	Multi-resolution Emission Inventory

MoE	Ministry of Environment
NCAP	National Clean Air Programme
NCD	Non-Communicable Disease
NCP	National Clean Air Programme
NCT	National Capital Territory
NH_3	Ammonia
NMMAPS	National Morbidity and Mortality Study
NMVOC	Non-Methane Volatile Organic Compounds
NO_x	Nitrogen Oxides
O_3	Ozone
PM	Particulate Matter
$PM_{2.5}$	Fine Particulate Matter
PMUY	Pradhan Mantri Ujjwala Yojna
RGGI	Regional Greenhouse Gas Initiative
SDG	Sustainable Development Goal
SIP	State Implementation Plan
SLCP	Short-Lived Climate Pollutants
SO_x	Sulfur Oxides
US	United States
US$	US Dollar
WDI	World Development Indicators
WHO	World Health Organization
WTP	Willingness-to-Pay



Executive Summary

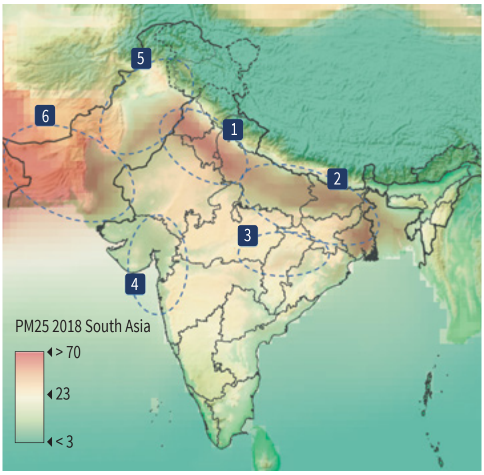
Nine out of the world's 10 cities with the worst air pollution are in South Asia. South Asians are exposed to extremely unhealthy levels of ambient air pollution, especially in densely populated, poor locations. The World Health Organization's (WHO) Air Quality Guideline recommends that concentrations of $PM_{2.5}$—small dust or soot particles in the air—should not exceed an annual average of 5 micrograms per cubic meter ($\mu g/m^3$). But in South Asia, nearly 60 percent of the population lives in areas where concentrations of $PM_{2.5}$ exceed an annual mean of 35 $\mu g/m^3$. In the densely populated Indo-Gangetic Plain, it is over 20 times the level that the WHO considers healthy (100 $\mu g/m^3$ in several locations).

Ambient air pollution is a public health crisis for South Asia, not only imposing high economic costs but also causing an estimated 2 million premature deaths each year. The health impacts of air pollution range from respiratory infections to chronic diseases, and from serious discomfort to morbidity and premature mortality. This drives up health-care costs, lowers productive capacity, and accounts for lost days worked.

Some of the main causes of air pollution in South Asia are unique to the region. Sources of air pollution that are less important in other parts of the world make substantial additional contributions to the pollution load in South Asia. These include: solid fuel combustion in the residential sector for cooking and heating; small industries, including brick kilns; burning high-emission solid fuels; the current management practices of municipal waste in the region, including burning plastics; the inefficient application of mineral fertilizer; fireworks; and human cremation. Significant air pollution in South Asia is also generated in agriculture, including through the generation of secondary particulate matter in the form of ammonia (NH_3) emissions from imbalanced fertilizer use and livestock manure that reacts with nitrogen oxides (NO_x) and sulfur dioxide (SO_2) gases from energy, industry, and transportation sources. In the western part of South Asia, natural sources, such as dust, organic compounds from plants, sea salt, and forest fires, are an important source of air pollution.

Controlling ambient air pollution is difficult without a better understanding of the activities that emit particulate matter and how emissions travel across locations. Air pollution travels long distances within South Asia, crossing municipal, state, and national boundaries, depending on wind, climatology, and cloud chemistry. At any given location, $PM_{2.5}$ in ambient air originates from several upwind sources extending over several hundred kilometers. This is especially true in and around the Indo-Gangetic Plain. For example, nearly 25 percent of the fine particulate matter that residents of the city of Patna are exposed to has its origin in a neighboring state. In many cities, such as Dhaka, Kathmandu, and Colombo, only one-third of the air pollution originates within the city.

Figure E.1. Six illustrative airsheds in South Asia based on fine particulate concentrations, topography, and fine particulate transportation between source regions



Source: Overlay by the World Bank project team and IIASA.
Note: Fine particulate concentrations are in micrograms per cubic meter ($\mu g/m^3$).

This report identifies six major airsheds in South Asia where spatial interdependence in air quality is high. Although air pollution travels far in South Asia, it does not uniformly disperse over the continent, but gets trapped in large "airsheds" that are shaped by climatology and geography. This report identifies six major airsheds in South Asia where spatial interdependence in air quality is high: (1) West/Central Indo-Gangetic Plain: Punjab (Pakistan), Punjab (India), Haryana, part of Rajasthan, Chandigarh, Delhi, Uttar Pradesh; (2) Central/Eastern Indo-Gangetic Plain: Bihar, West Bengal, Jharkhand, Bangladesh; (3) Middle India: Odisha/Chhattisgarh; (4) Middle India: Eastern Gujarat/Western Maharashtra; (5) Northern/Central Indus River Plain: Pakistan, part of Afghanistan; and (6) Southern Indus Plain and further west: South Pakistan, Western Afghanistan extending into Eastern Iran.

This report uses a detailed geospatial model to quantify particulate matter emissions and how they disperse in the atmosphere. The Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model employed in this report computes the annual averages of $PM_{2.5}$ concentrations to which residents of every state/province (hereafter referred to as "region") of South Asia are exposed. It also computes $PM_{2.5}$ exposure at the city level, and determines the place and the sector of origin of this ambient air pollution in each region and city.

The report shows that current policy measures will only be partially successful in reducing $PM_{2.5}$ concentrations across South Asia, even if fully implemented. The report's model estimates that air quality policy measures in place as of 2018 can have a significant impact on the trajectory of air pollution in South Asia, if fully implemented and effectively enforced. For example, primary fine particulate matter (such as soot and mineral dust) would decline by 4 percent rather than grow by 12 percent between 2018 and 2030, regionwide. But large parts of South Asia—accounting for about two-thirds of its total population—will still miss the least-ambitious WHO Interim Target 1 of 35 µg/m^3 concentration.

Even if all technically feasible measures were fully implemented, parts of South Asia would still not be able to meet the WHO Interim Target on their own by 2030 because of the spatial interdependence of air quality. Suppose the Delhi National Capital Territory (NCT) were to fully implement all technically feasible air pollution control measures by 2030, while other parts of South Asia continued to follow current policies. This report's model predicts that the Delhi NCT area would still not meet the WHO Interim Target because the inflow of pollution from outside regions and from natural sources already exceeds 35 µg/m^3. It would, however, meet the WHO Interim Target if other parts of South Asia also adopted all feasible measures. This is also the case with many other cities in South Asia, especially those in the Indo-Gangetic Plain.

Accounting for the interdependence in air quality within airsheds in South Asia is necessary when weighing alternative pathways for pollution control. The report analyzes four alternative pathways (hereafter referred to as "scenarios") for reducing air pollution in South Asia (Table E.1). These scenarios vary in the ambition of their air pollution targets and the degree to which their strategies for achieving those targets provide for regional coordination.

Pollution control scenarios that do not leverage spatial interdependence in air quality are relatively expensive. Scenario 1, which scales up measures already in place in parts of South Asia to other regions, would reduce average $PM_{2.5}$ exposure in South Asia in 2030 to about 37 µg/m^3. This is a bigger reduction than that achieved by full implementation of 2018 policies because all regions undertake a common set of pollution control measures. Scenario 2, which entails the full implementation of all technically feasible emission controls everywhere across South Asia, would cut average $PM_{2.5}$ exposure in South Asia in 2030 to 17 µg/m^3. Not surprisingly, this would be the biggest reduction among all four scenarios. But this scenario is also the most expensive one because it employs all feasible measures regardless of their cost: it has an annual cost of reduced exposure per µg/m^3 of US$2.6 billion.

Focusing on hotspots would reduce mean exposure to 26 µg/m^3. Focusing on the hotspots, while leveraging the spatial dependence of air pollution between hotspots and their upwind areas (Scenario 3) would reduce the mean exposure in South Asia to 26 µg/m^3. The approach underlying this scenario reduces costs significantly by substituting excessively costly measures at hotspots by more cost-effective measures in areas upwind of hotspots, with an estimated cost of US$780 million per µg/$m^3$ of reduced exposure. Thus, this scenario would achieve a significantly greater reduction in air pollution than Scenario 1, but at a comparable cost.

Table E.1. Four modeled scenarios for AQM in South Asia

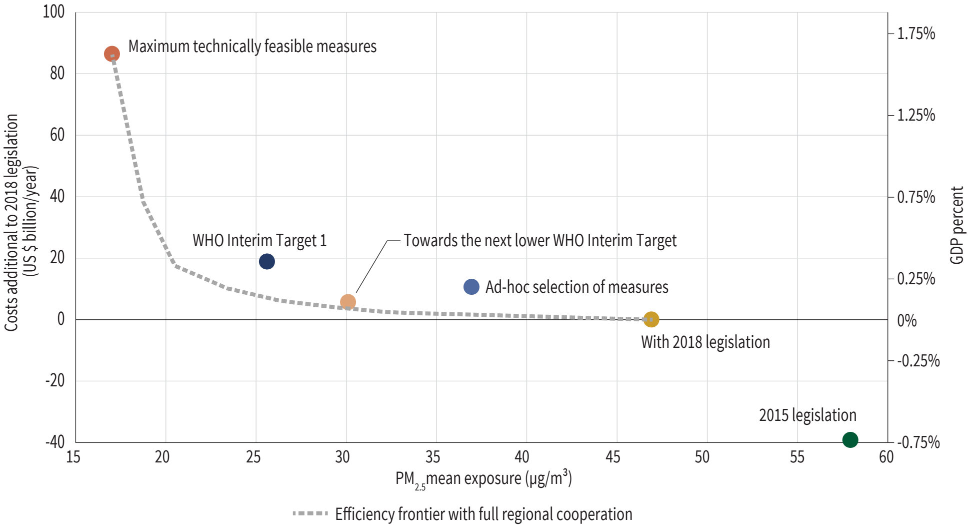
Scenario 1: Ad-hoc selection of measures	Scenario 2: Maximum technically feasible emissions reductions
• Scaling-up of measures that are currently taken in parts of South Asia to all its regions • Each region acts independently	• Full implementation of all technical emission controls that are available on the world market • No regional coordination
Scenario 3: Compliance with WHO Interim Target 1 everywhere in South Asia	**Scenario 4: Toward the next lower WHO Interim Target**
• In all regions, mean population exposure is reduced to 35 μg/m^3 • Regions cooperate to the extent they are contributing to pollution hotspots	• Reduce the present difference of $PM_{2.5}$ exposure by 90% to the next lower WHO Interim Target in each region • Full coordination across regions to maximize cost-effectiveness

By cutting exposure toward the next lower WHO Interim Target in each region with full coordination across regions, the mean exposure in South Asia would decline to 30 μg/m^3 in a cost-effective manner. Under Scenario 4, in which each region cuts exposure to 90 percent of gap with the next lower WHO Interim Target, while *fully* leveraging spatial interdependence, the mean exposure in South Asia would decline to 30 μg/m^3. The approach followed in this scenario is the most cost-effective, at US$278 million per μg/$m^3$ of reduced exposure. This is because it employs the least-cost combination of measures within airsheds: it avoids implementing costly measures at one location if the same impact can be achieved by a less costly action at another location in the same airshed.

Scenario 4 also leverages sectoral differentiation to improve the cost-benefit ratio of pollution control measures. Compared with Scenario 2, where all technically feasible measures are implemented, Scenario 4 leans more heavily on: lower-cost options in the household sector with cleaner cookstoves and liquified petroleum gas (LPG) solutions; and the control of secondary particulate matter, particularly through agricultural sector interventions, such as balanced fertilizer application and manure management. The scenario also focuses on managing the burning of municipal waste.

Regional cooperation could thus help implement cost-effective joint air pollution strategies that leverage spatial interdependence in air quality. As the scenario modeling shows, if regions within South Asia were to work toward their air quality targets independently of each other, those with relatively limited options for improving air quality may be forced to undertake costly measures. Meanwhile, those with good options for improving air quality may not exercise some of those options because they do not account for the benefits to other regions from doing so.

Figure E.2. Exposure reductions and costs of associated emission controls for the four modeled scenarios in South Asia region in 2030



Source: GAINS calculations/IIASA (2021).
Note: Exposure reduction is in micrograms per cubic meter. Costs are in US$ billions of USD and percent of GDP.

Regional coordination could also help break deadlocks in policy action by increasing certainty about the payoffs from different policy scenarios. Because of the spatial interdependence in air quality, each region's expectations about future air quality if it were to take certain pollution control measures depend on expectations about actions taken by others. Policy makers may choose to delay costly actions because of uncertainty about future air quality. Regional coordination may help speed up action by firming up expectations about future air quality.

The health and economic benefits of air pollution control

Steps to reduce ambient and household air pollution could significantly reduce premature deaths. The four scenarios outlined in the report involve policies to reduce emissions of ambient $PM_{2.5}$ from stationary and mobile sources, such as power plants, factories, and motor vehicles, and also reduce the number of households burning solid fuels. Deaths avoided in the year 2030 due to reductions in $PM_{2.5}$ according to the four scenarios range from 276,000 to 1,270,000, and the average cost per life saved for each scenario varies from US$7,600 to US$68,000. The impacts of these reductions in $PM_{2.5}$ on premature mortality are measured from baseline values of ambient and household air pollution in 2030.

The effectiveness of air pollution control policies in reducing premature deaths varies greatly across policies and within regions. Under Scenario 1, which reflects traditional air pollution control measures, 276,000 premature deaths are avoided, but it only reduces baseline deaths caused by air pollution in Nepal, Pakistan, and Sri Lanka by 3–4 percent. The policies are slightly more effective in India, reducing deaths by 15 percent in the Indo-Gangetic Plain and, on average, by 16 percent in the rest of India. In Bangladesh, deaths are reduced by 7 percent. These policies come at a cost per life saved of US$38,000. In contrast, the policies in Scenario 2 are much more effective, reducing premature deaths by 1,270,000, or 55–85 percent across countries. However, the average cost per life saved by these policies is US$68,000.

The analysis shows that Scenario 4, with a $PM_{2.5}$ level of 30 μg/m^3, has the lowest per capita cost of averting premature deaths and the highest benefit-to-cost ratio for morbidities. Polices under this scenario save more lives—more than 750,000 annually—than policies in Scenario 3, and at a much lower cost per life saved, at US$7,600, or only 11 percent of the cost under Scenario 2. Reductions in baseline deaths resulting from these lower cost policies show geographical variation. Specifically, the reductions in Sri Lanka and non-Indo-Gangetic Plain India are larger than the reductions from the set of policies in Scenario 3, although the reduction in deaths is 10–15 percentage points lower in other regions of South Asia. The lower cost per life saved by policies under Scenario 4 is achieved by relying on reductions in the percentage of households burning solid fuels, which should also benefit more women and children.

A roadmap toward airshed-wide air quality management

Though progress has been made in legislation and planning for AQM, South Asia is not on track to reach even the modest WHO Interim Target. That target of 35 μg/m^3 is still seven times the concentration that the WHO considers healthy. The reason of insufficient progress is that, currently, the focus of interventions is almost completely on mitigating pollution generated within cities. Most countries in South Asia have imposed varying emission standards for vehicles and have mandated low-NO_x burners for power plants and filters for some large industrial boilers. To achieve more progress—and more cost-effective progress—the policy focus should broaden into other sectors, especially small manufacturing, agriculture, residential cooking, and waste management, which are important sources of air pollution in South Asia. Along with the broadening of the sectoral focus, coordination of abatement activities within larger areas (within the airsheds) is needed.

This report shows that optimal solutions to reach clean air are economically feasible in South Asia, but that the implementation of these policies is challenging. The report demonstrates that economic benefits of these optimal policies exceed the economic costs by a large margin. However, implementation of these policies requires coordination that incentivizes cooperation across different jurisdictions and coordination between nations, as airsheds do not recognize national borders. Under the predominant wind direction from the northwest to the southeast, 30 percent of the air pollution in the Indian state of Punjab comes from Punjab Province in Pakistan and, on average, 30 percent of the air pollution in the largest cities of Bangladesh (Dhaka, Chittagong, and Khulna) originates in India. During parts of the year, substantial pollution flows in the other direction across borders. Optimal AQM also requires changes in the behavior of millions of farmers, small enterprises, including small-scale brick kilns, and households. Such behavioral change is not easy to achieve in practice. The journey toward that optimal solution is best guided by the following roadmap, which breaks down the journey in three phases, each consisting of three steps.

Phase I: More and better monitoring and improved institutions

Cost-effective AQM requires more comprehensive monitoring, also outside cities, enhanced scientific capacity, a shared knowledge base, and strong cooperation between governments.

Step I.1: Widespread installation of sensors and the sharing of data

- **Emissions inventories are currently incomplete in South Asia.** South Asia should move toward a comprehensive, unified inventory for the region that represents the full range of relevant emission sources, instead of relying on each city or state to develop its own individual methodology.
- **Transparency and accessibility are important components of a monitoring system.** The accessibility of data on unified platforms is critical to the sharing of knowledge and the building of trust across jurisdictions. Public awareness of air quality data can also help build support for AQM.
- **Monitoring systems need to be maintained and updated on an ongoing basis.** Technology will continuously improve, perhaps changing which policy choices are most cost-effective or even rendering some policy action obsolete.

Step I.2: Creation of credible scientific institutes that analyze airsheds

- **Scientific capacity in South Asia is currently well-developed in atmospheric science, but still relatively underdeveloped when it comes to capturing the region-specific sources of air pollution.** Further development of analytical capacity should include research of the health impacts, and the analysis of economic incentives and behavioral adjustments. In all these areas, there is a knowledge gap regarding the influence of specific circumstances in South Asia.
- **Scientific capacity should not be centralized, but rather distributed across the region.** To enhance the credibility and salience of scientific information among the

stakeholders of airsheds, and to ensure more equal representation and ownership across countries and jurisdictions, a South Asia-wide scientific community on AQM should facilitate communication between experts across administrative boundaries and develop a scientific consensus on critical issues.

Step I.3: Toward a whole-of-government approach

- **The capacity of ministries of the environment must be strengthened.** These ministries have the principal mandate to manage air-quality programs, but they have neither the financial resources nor sufficient staff required for the needed coordination of environmental policies in agriculture, energy, industry, rural development, transportation, and urban development.
- **A strong and central technical role of ministries of the environment should be complemented with a whole-of-government approach.** AQM can have far-reaching consequences for other policy areas, from energy and climate policy to growth strategy and distributional policies. The report shows how synergies between AQM and climate policies can be exploited. The report also shows that there is a significant overlap between local air quality and poverty in South Asia, and that abatement efforts can have distributional impacts. To ensure consistency with the broader development strategy, a whole-of-government approach to AQM is needed.

Phase II: Additional and joint targets for cost-effective abatement

Airshed-wide AQM will automatically include low-cost abatement of more sources of air pollution. Once the focus broadens beyond cities, other emissions, which are important especially in South Asia, can be reduced. These include emissions from solid fuel use in households, from brick kilns and ovens in other small industries, from agriculture, and from open burning of solid municipal waste.

Step II.1: Switching to the use of cleaner cookstoves

- **Cleaner cookstoves are cost effective, but implementation challenges remain.** Despite the effectiveness of clean cookstoves to improve health, three main challenges to long-term adoption remain: (i) initial and maintenance costs; (ii) knowledge and beliefs; and (iii) compatibility with end users. These challenges imply that economic support and information, in addition to adequate price signals, are key in achieving the adoption of clean fuel technology by mostly poor, rural households.

Step II.2: Reduction of emissions from agriculture and brick kilns

- **Burning of fields results in high seasonal peaks in air pollution throughout airsheds.** Recent evidence from India shows that cash transfers as payments for ecosystem services can reduce agricultural burning by up to 80 percent.
- **Subsidies for fertilizers, another cause of air pollution, should be reconsidered.** Other interventions can also successfully lower fertilizer use without compromising productivity. For example, Bangladesh's simple rule-of-thumb training using colored leaf charts lowered fertilizer use by 8 percent without compromising yields.
- **Large-scale intensive livestock operations can prevent emissions through the scrubbing of ventilated air both into and out of animal housing areas.** Various types of air purification systems exist, including combination filters that remove more than one pollutant. Abatement measures for animals not contained within housing include a switch to low-nitrogen feed, the covered storage of manure, and application of manure on farms with technology designed to reduce ammonia emissions.
- **Less polluting and more viable brick kiln technologies are available but slow in being adopted.** Many brick kilns in South Asia are very small units using old technologies, with inefficient combustion of coal and agricultural waste. Existing kilns can be converted to improved "zig-zag kilns" that produce less emissions and are more efficient in brick production. However, the adoption rate of zig-zag kilns remains low, implying that behavioral change requires more than price incentives.

Step II.3: Improved municipal waste management

- **Municipal waste management represents one of the most cost-effective potential interventions in the region.** In many cities in South Asia, no waste collection exists and even in cities with high collection rates, the segregation of waste and recycling hardly exist. Recycling, controlled incineration, composting for biodegradable waste, and managed landfills not only reduce air pollution, but also generate revenues, for example by recovering precious or rare earth metals from electronic components.

Phase III: Mainstreaming air quality in the economy

In the long run, pricing of externalities through taxation or tradable emission permits should play a central role in AQM. In the short run, mandated emission standards, authorized filters or technologies, and bans of certain activities are the most effective methods to reduce air pollution. However, these methods come with disadvantages. Emission standards reduce emissions per unit of economic activity, but they do not curb the total amount of polluting activity. Emission standards also do not incentivize the private sector to develop technologies that reduce pollution to levels below the mandated standards. If pollution has a cost, in the form of *a tax or a price of an emission permit, total emissions are reduced more, and innovation is more stimulated. With these economic incentives, it will also be easier to mobilize private and public funds to reduce air pollution.*

Step III.1: Taxation of air pollution

- **Taxation of activities that release pollutants will make cleaner technologies more competitive.** Likewise, subsidies can encourage the use of clean industry and technology that do not harm air quality. Currently, most examples of taxes on air pollutants are found in developed economies. These taxes target primarily GHGs or cover only one type of source (typically, large power plants or large firms in high-polluting industries). However, developing countries are increasingly experimenting with direct taxes on pollutants. China has an Environmental Protection Tax on $PM_{2.5}$ precursors (SO_2, NO_x and soot). Mexico imposed a carbon tax in 2014. It applies to CO_2 emissions from all sectors and covers all fossil fuels except natural gas. In October 2021, Indonesia passed a law to introduce a carbon tax on coal-fired power plants.

Step III.2: Creation of markets for emission-permit trading

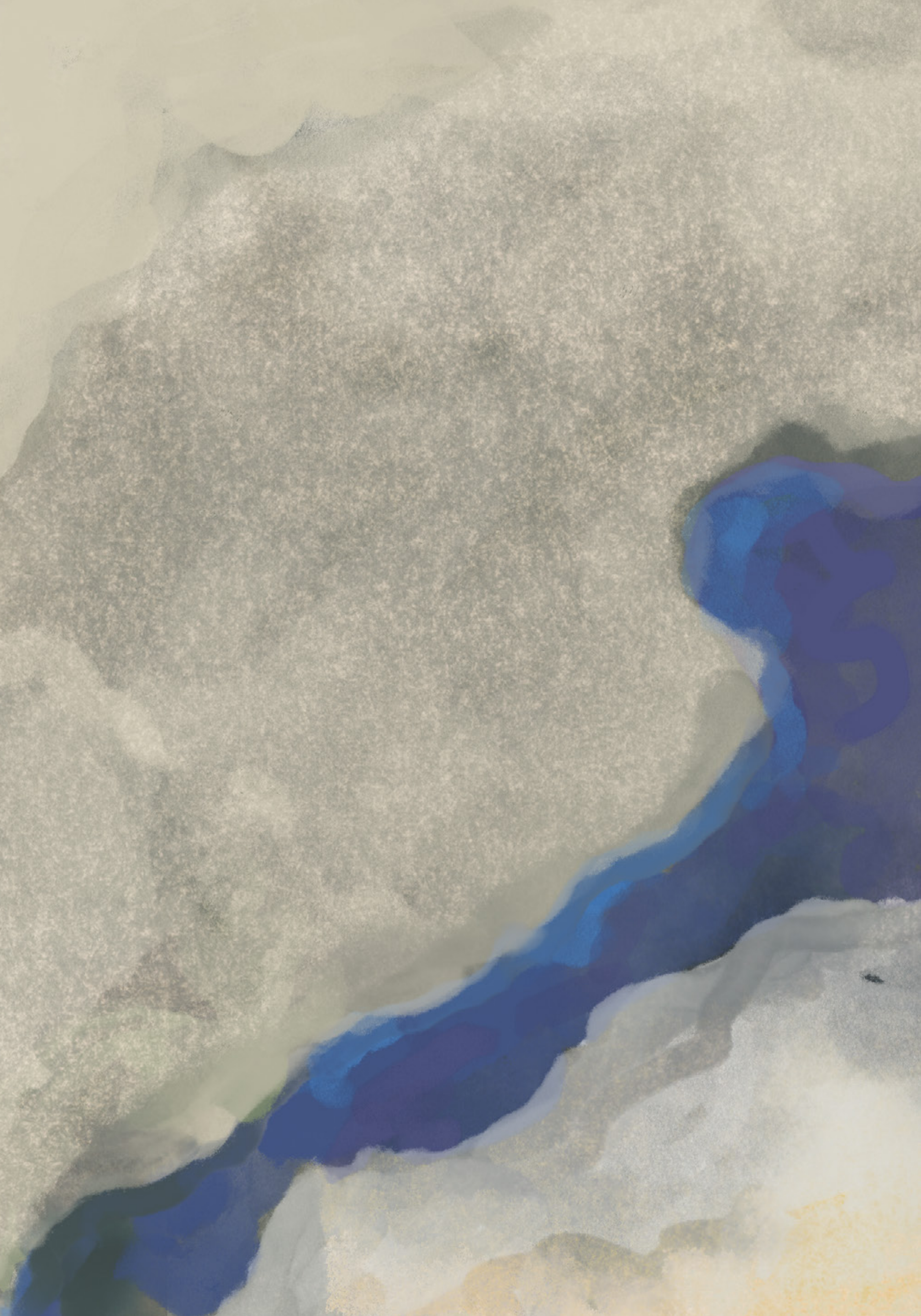
- **Tradable emission permits can have significant advantages.** An airshed-wide system of tradable emission permits gives firms throughout the airshed more flexibility to adjust their emissions and incentives to innovate and it automatically provides pecuniary compensation across jurisdictions for abatement efforts. Most examples of these permit markets are in developed countries, but similar programs are now being piloted or under consideration in Mexico, China, Thailand and Turkey.
- **Recent evidence from a pilot of permit trading in India is encouraging.** The state of Gujarat recently introduced emission permit trading among 317 high-polluting plants. A critical precondition for this scheme was the installation of a robust monitoring systems in the participating firms. The pilot has been evaluated through a randomized control trial, which shows that it reduced emissions significantly and at low-cost relative to the existing command and control regulation.

Step III.3: Mobilization of funding

- **An important advantage of the use of economic incentives is that they can mobilize funds from the private and public sectors for clean technologies.** When the negative externalities of air pollution are incorporated into the price of technologies, it becomes profitable for the private sector to invest in clean technologies. The larger the area that imposes taxes, the easier it is for the private sector to invest at scale. Revenues from taxes on pollutants or from sale of emission permits generate the fiscal space to create public funds that support abatement activities. Such funds can play an important role in enticing cooperation within an airshed across jurisdictions.

- **The synergies between reductions in air pollution and climate change policies can help mobilize international funds.** Strong synergies exist between meeting cleaner air target and meeting commitments to reduce GHG emissions. Those synergies can mobilize international funds that can support AQM. Some of these funds come from multilateral development banks, scaling up existing programs that link financing to the achievement of air quality improvement targets.

Achieving cleaner air in South Asia in a cost-effective way is possible, but the road ahead is not an easy one. This analysis in this report shows that, from a technical point of view, direct economic gains of better air quality exceed the abatement costs needed to reduce air pollution. However, it is not easy to achieve these optimal solutions. It requires the building of better monitoring systems, more scientific capacity, and better coordination between governments. It requires behavioral change among farmers, small firms, and households. It requires experiments with greening of tax systems and with tradable emission permits. International experience has to be finetuned to the specific conditions in South Asia. It requires cross-border coordination in South Asia. In particular, the latter is far from straightforward, but the time is now to put conditions in place for such cross-border cooperation and the time is now to travel the road to cleaner air. The rewards of advancing on the road are high as the economic and social costs of lack of progress are hard to overestimate.



CHAPTER 1

Introduction

South Asia suffers from extreme air pollution. Nine of the ten cities with the most severe air pollution in the world are in South Asia. In the northern part of the region, with a high concentration of poor households, the average annual concentration of fine particulate matter ($PM_{2.5}$) is around 16 times the maximum that the World Health Organization (WHO) considers healthy (Figure 1.1). In addition to high ambient air pollution, poor households also experience high levels of indoor air pollution, caused by the use of solid fuels for cooking and heating.

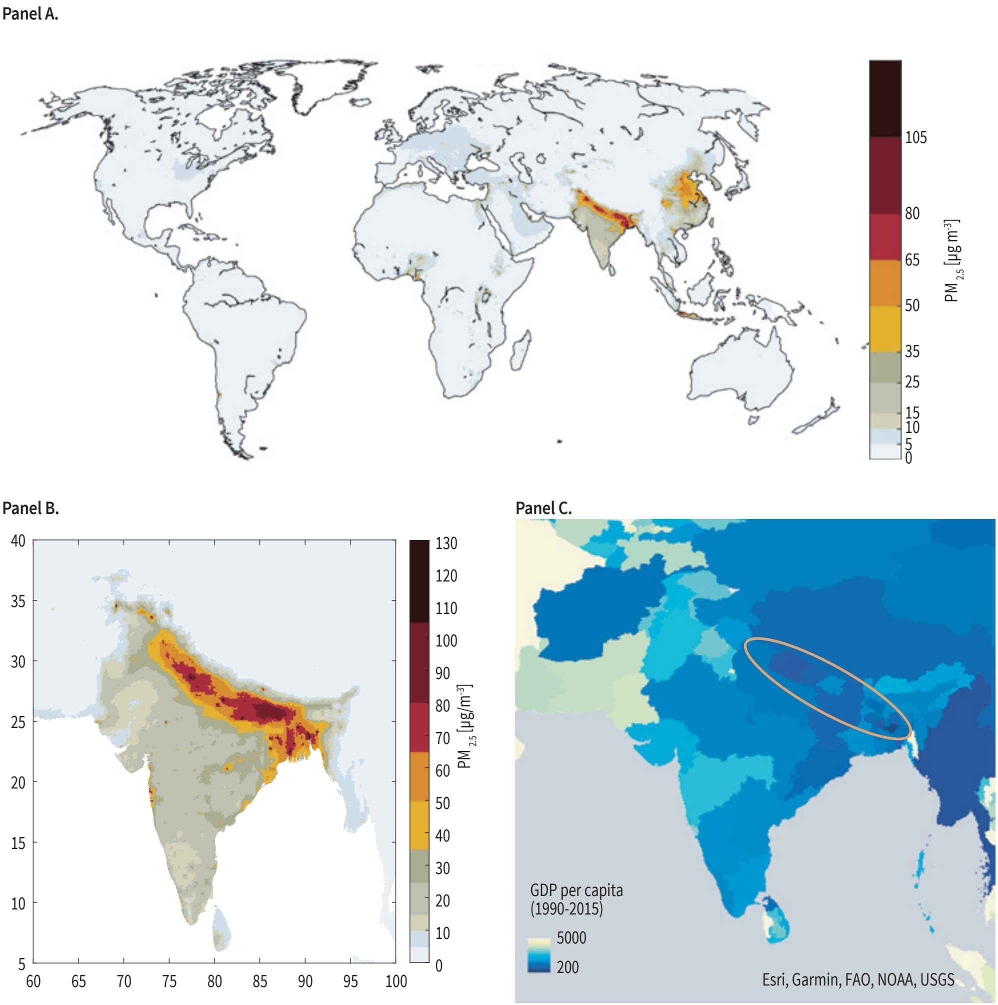
The exposure to extreme air pollution has severe health impacts. Current air pollution is estimated to cause over 2 million premature deaths each year in South Asia. $PM_{2.5}$ is now also understood to be an important causative factor in many non-communicable health risks. For newborns, it has been associated with low birthweights and premature births. For children, it can lead to asthma, stunting, and reduced cognitive development, with lifelong consequences. In adults, $PM_{2.5}$ is associated with chronic obstructive lung disease, ischemic heart disease, lower respiratory infections, lung cancer, strokes, and type II diabetes. For the elderly, a correlation with dementia has been established.

Air pollution comes with economic costs. Increased morbidity raises health-care costs and reduces the number of days worked per person. Stunting leads to lower productivity later in life. Firms and skilled workers might choose not to locate in areas with severe air pollution (World Bank 2018). Potentially, factories could be temporarily closed, or traffic could be temporarily limited during periods of peak pollution.

South Asian countries have made strides in strengthening air quality management (AQM) programs, but more work is needed. Recent years have seen a wave of policy responses introduced to combat air pollution, including the Draft Bangladesh Clean Air Act, India's National Clean Air Programme (NCAP), and the National Electrical Vehicles Policy in Pakistan. These recent policy changes will allow economies to grow without corresponding increases in air pollution. Further measures beyond these decoupling efforts will, however, be necessary for South Asian countries to reduce air pollution.

To effectively reduce air pollution, cooperation across jurisdictions is needed. Less than half of the air pollution in the major cities of South Asia is produced within the cities themselves.

Figure 1.1. Air pollution in South Asia is significantly worse in some parts of the region: The northern part of South Asia, where poverty is high, suffers from the highest level of air pollution

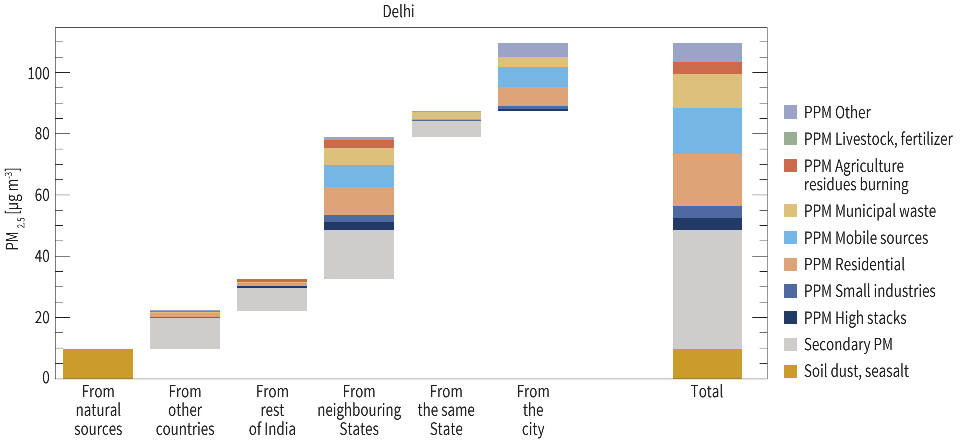


Source: Panel A: GAINS calculations/IIASA (2021); Panel B: GPvW4; Panel C: Kummu, Taka, and Guillaume (2020).
Note: Fine particulate concentrations are in μg/m^3. GDP per capita is in US$.

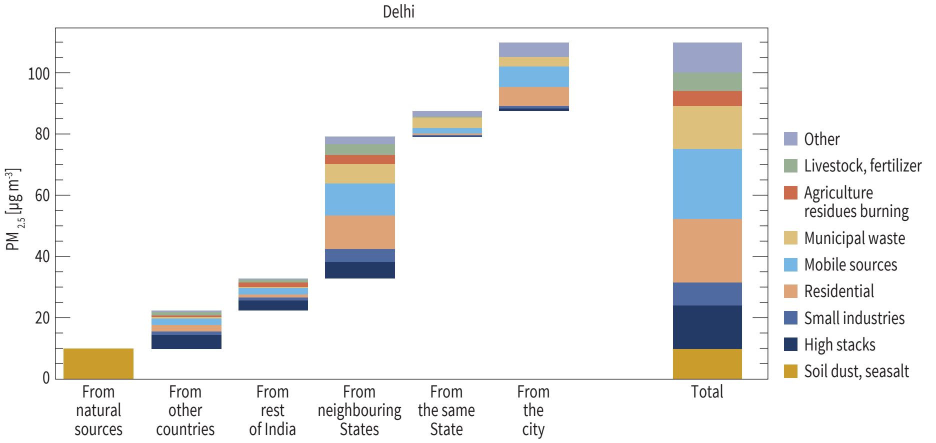
At the same time, air pollution that originates in cities spreads well beyond the city borders. Air pollution is transported over long distances, and then trapped in large “airsheds” shaped by climatology and geography. As the air pollution in a location within an airshed arrives from different locations to that airshed, the sources of air pollution are diverse, ranging from powerplants, large factories, and traffic, to agricultural emissions, waste burning, brick kilns, and cooking. Figure 1.2 shows the variety of sources in Delhi National Capital Territory (NCT), and the significant contributions from locations beyond the Delhi NCT. Much of the focus of

Figure 1.2. Delhi National Capital Territory, spatial and sectoral origin of fine particulate matter in ambient air, 2018

A. Total sector contributions, Delhi NCT



B. Primary and secondary PM, Delhi NCT



Source: GAINS calculations/IIASA (2021).
Note: Fine particulate concentrations are in µg/m³.

air pollution management in South Asia has been on a city level and a few major polluters within the city. For more effective AQM, coordination within airsheds is needed, while the focus should widen to a broader group of polluters.

This study is organized as follows: Chapter 2 provides a picture of the various sources of air pollution in South Asia, and how these sources interact and form airsheds. Chapter 3 presents various alternative scenarios for cost-effective pollution control measures and studies the costs of these scenarios as compared with existing legislation. The health impacts arising from these four scenarios are calculated in Chapter 4, along with the estimated economic benefits of reductions in air pollution. Chapter 5 discusses policy recommendations, including the development of airshed-scale management strategies. Such strategies will require more information and transparent incentives for cooperation across jurisdictions.

References

GHDx. 2021. Global Health Data Exchange. Institute for Health Metrics and Evaluation. Seattle, WA. http://ghdx.healthdata.org (accessed July 15, 2021).

Kummu, Matti, Maija Taka, Joseph H.A. Guillaume. 2020. Data from: Gridded global datasets for Gross Domestic Product and Human Development Index over 1990-2015, Dryad, Dataset, https://doi.org/10.5061/dryad.dk1j0 (accessed November 14, 2022).

CHAPTER 2

Air Quality in South Asia – A Regional Picture of the Sources of Air Pollution

The study employs a series of well-established scientific tools and methods that provide a holistic perspective on air quality in South Asia, and explores the costs and benefits of different policy interventions to reduce air pollution in the region. As a starting point for the subsequent strategic analyses, a comprehensive assessment of the current state of air quality in South Asia reveals the most important sources of pollution, and how these affect air quality in cities and regions (provinces/states) throughout South Asia.

The GAINS model[1] is employed to provide a holistic perspective on the chain of air pollution in the region (Amann et al., 2011). Starting from the socio-economic drivers, the GAINS model quantifies emissions and their dispersion in the atmosphere and estimates their multiple impacts on air quality and human health. Importantly, the model assesses the improvements offered by about 2,000 proven measures to reduce emissions, estimates their costs, and quantifies their side-effects on greenhouse gas (GHG) emissions. The cost-effectiveness analysis of the model identifies packages of measures that deliver exogenously specified policy targets on air quality and/or GHG emissions at least cost (Figure 2.1). Details of the modeling exercise are in Annex A.2.1.

Some of the key aspects of the modeling approach are:

- To inform efforts to protect public health in an economically effective way, the modeling employs the **annual average population-weighted mean exposure to ambient $PM_{2.5}$** as the central metric. It should be noted, however, that mean population exposure is lower than the highest concentrations measured at hotspots, which are relevant for establishing compliance with ambient air quality standards.

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[1] The GAINS model is an analytical framework for assessing future potentials and costs for reducing air pollution impacts on human health and the environment while simultaneously mitigating climate change through reduced greenhouse gas emissions. It explores synergies and trade-offs in cost-effective emission control strategies to maximize benefits across multiple scales.

Figure 2.1. Information flow in the GAINS model

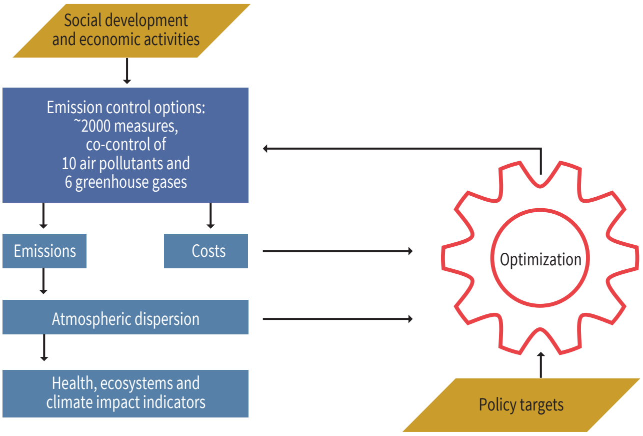
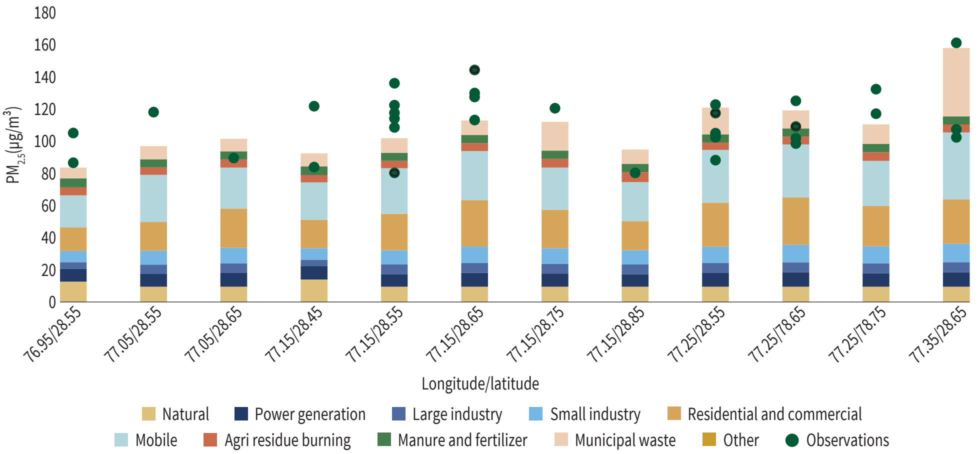


Figure 2.2. Modeled average fine particulate concentrations by source for 10 x 10-kilometer grid cells compared with observations from monitoring stations located within the grid cells in Delhi NCT, 2018



Source: GAINS calculations/IIASA (2021) and CPCB (2020).
Note: The x-axis presents longitude and latitude. Fine particulate concentrations are in μg/m^3.

- The model computes grid average PM$_{2.5}$ concentrations throughout the domain at a **10 x 10-kilometer spatial resolution**. With these data, the mean population exposure over the entire population in an administrative region can be computed. It is necessary, however, to ensure that the modeled data are validated with monitoring data from various monitoring stations (Figure 2.2) to ensure good predictability of future scenarios.

2.1 Key features of air pollution in South Asia

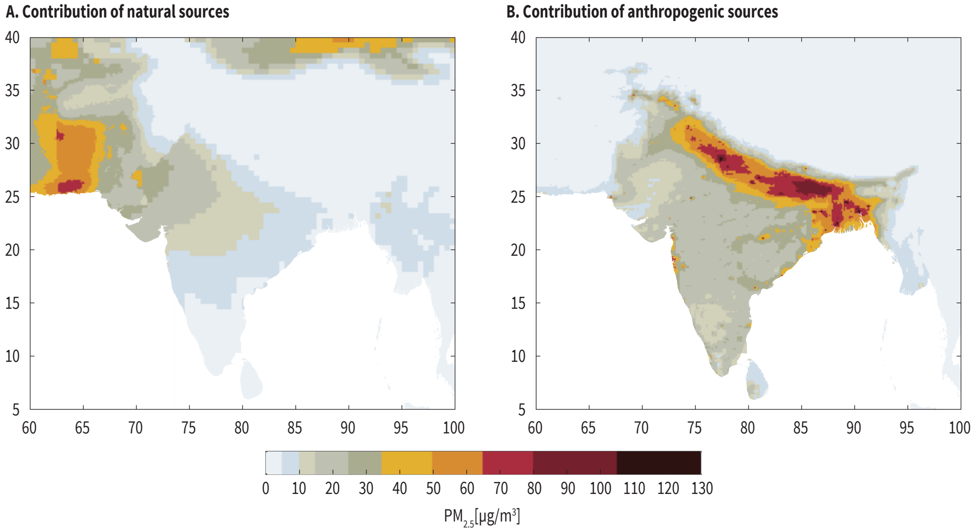
Beyond their contributions to human exposure to $PM_{2.5}$ in ambient air, some emission sources cause additional health impacts through exposure in indoor environments. While the study addresses the management of pollution in ambient air, several emission sources cause additional health impacts through the exposure pathway in indoor environments. Severe health impacts are estimated to result from exposure to emissions from the combustion of solid fuels for cooking and heating in households without proper ventilation, adding to the high health burden from exposure to pollution from these sources in ambient air. The quantification of the interplay of household and ambient exposure is discussed further in Chapter 4, which provides estimates of the total health impacts from all sources that generate ambient air pollution.

While there is considerable diversity in ambient levels of $PM_{2.5}$ across South Asia, average annual concentrations exceed the WHO's Air Quality Guideline of 5 $\mu g/m^3$ by a wide margin throughout the region. Concentrations of $PM_{2.5}$ vary significantly across South Asia. Generally, the highest levels occur in the Indo-Gangetic Plain, where annual mean concentrations exceed the WHO Guideline by a factor of 20 and more. Further concentration peaks appear in many cities, as well as in desert areas. In contrast, concentrations are much lower in the southern part of the region, although there they also surpass the WHO Guideline by a wide margin.

In wide areas of South Asia, natural sources contribute significantly to total $PM_{2.5}$ concentrations in ambient air in addition to anthropogenic sources. In some parts of South Asia, rather large contributions to $PM_{2.5}$, in both relative and absolute terms, originate from natural sources, from soil dust in arid regions (Figure 2.3, left panel). Some of the natural sources of air pollution are organic compounds from plants and sea salt. Other natural sources are released during such catastrophes as volcanic eruptions and forest fires. *The importance of natural sources that cannot be immediately influenced by policy interventions has to be kept in mind when setting policy targets for total $PM_{2.5}$ concentrations in ambient air, either in absolute terms such as in ambient air quality standards, or relative ones, for example, percentage reductions of total $PM_{2.5}$ concentrations relative to a base year.*

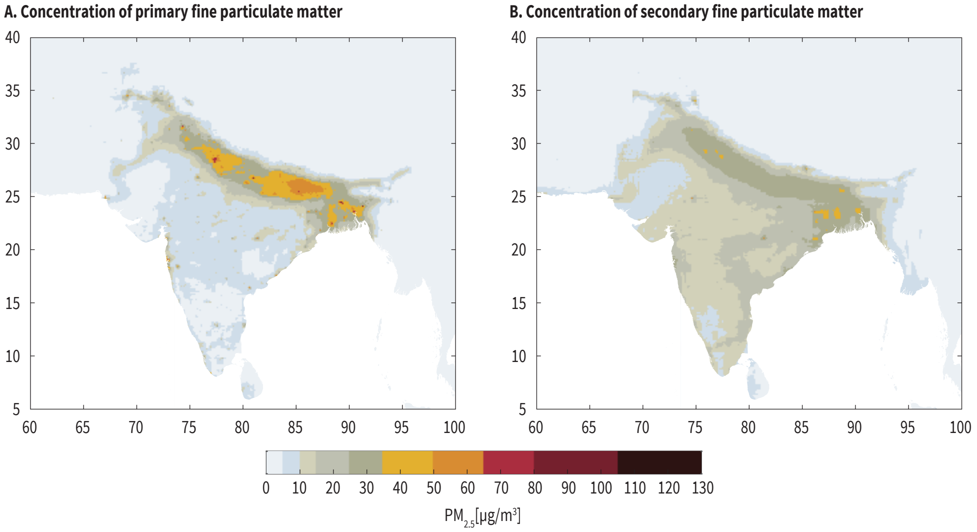
Throughout South Asia, secondary $PM_{2.5}$ particles, formed through chemical reactions in the atmosphere from gaseous precursor emissions, account for a sizable fraction of total $PM_{2.5}$ concentrations in ambient air. Fine particulate matter in ambient air is composed of so-called primary particles, such as soot and mineral dust, which are directly emitted, as well as secondary particles/aerosols, which are formed in the atmosphere in chemical processes from precursor emissions of SO_2, NO_x, NH_3 and non-methane volatile organic compounds (NMVOC). Over large areas in South Asia, such secondary particles/aerosols account for a

Figure 2.3. Contributions of natural and anthropogenic emission sources to ambient concentrations of fine particulate matter, 2018



Source: GAINS calculations/IIASA (2021).
Note: Fine particulate concentrations are in µg/m³.

Figure 2.4. Concentrations of primary and secondary fine particulate matter originating from human activity, 2018



Source: GAINS calculations/IIASA (2021).
Note: Fine particulate concentrations are in µg/m³.

sizable fraction of total $PM_{2.5}$ in ambient air, often exceeding the contributions of primary particles from anthropogenic sources (Figure 2.4). This has major implications for AQM: effective strategies need to address the full range of emissions, including those of precursors of secondary particles/aerosols. *Strategies focused on primary particles/aerosols can only achieve limited reductions of total $PM_{2.5}$ concentrations in ambient air and are unlikely to deliver cost-effective improvements as they neglect potential low-cost options for limiting emissions of precursors of secondary $PM_{2.5}$.*

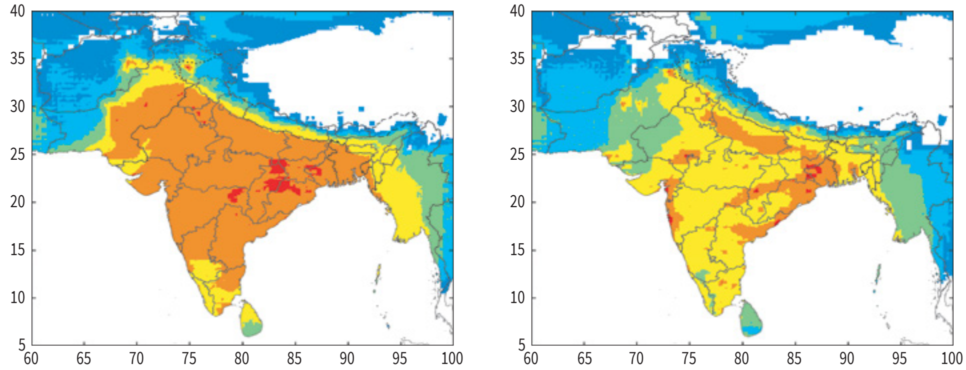
In addition to emission sources that are common throughout the world, there are activities specific to South Asia that contribute large amounts of $PM_{2.5}$ in ambient air. As in many other regions of the world, power generation, large-scale industries, and mobile sources are responsible for significant shares of total $PM_{2.5}$ concentrations in South Asia, together often exceeding the WHO Guideline value. However, there are other sources that are less important in other world regions that make substantial additional contributions to the pollution load in the South Asia region, on top of the sources that are most prevalent across the world. These include, among others: solid fuel combustion in the residential sector for cooking and heating; small industries, including brick kilns; burning high-emission solid fuels; the current management practices of municipal waste in the region, including burning plastics; the inefficient application of mineral fertilizer; fireworks; and human cremation. Contributions of these source categories to total $PM_{2.5}$ concentrations in ambient air in South Asia are shown in Figure 2.5. *As a result, policy interventions that focus only on emission sources that are prominent across the world would only have a limited impact on total $PM_{2.5}$ concentrations in the South Asia region, as they miss the large contributions caused by South Asia-specific pollution sources.*

Due to the diversity of sources that contribute to $PM_{2.5}$ in ambient air in South Asia, particulate matter at any given receptor site needs to be traced to many different sectors. While quantitative shares differ across cities and provinces/states due to local topographic, meteorological, and economic factors, except for isolated pollution hotspots, no one sector can be identified as the single source responsible for the majority of $PM_{2.5}$ at any given location (Figures 2.6 to 2.8).

Due to this multi-sectoral character of the sources of air pollution in South Asia, effective air quality management, in addition to the sources that have been in the focus of past efforts, i.e., road transport and large point sources, will need to involve other sectors that are important in specific sub-regions, such as household energy uses, small industries (e.g., brick kilns), waste management, and agricultural activities.

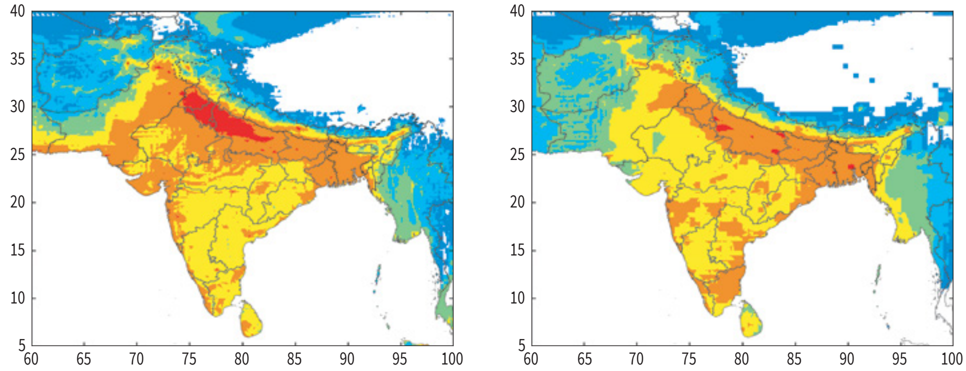
$PM_{2.5}$ particles in the atmosphere can be carried through the air by the wind for several hundred to a few thousand kilometers before they are deposited on the surface. Thus,

Figure 2.5. Concentrations of small particulate matter in ambient air originating from key emission sectors, 2018



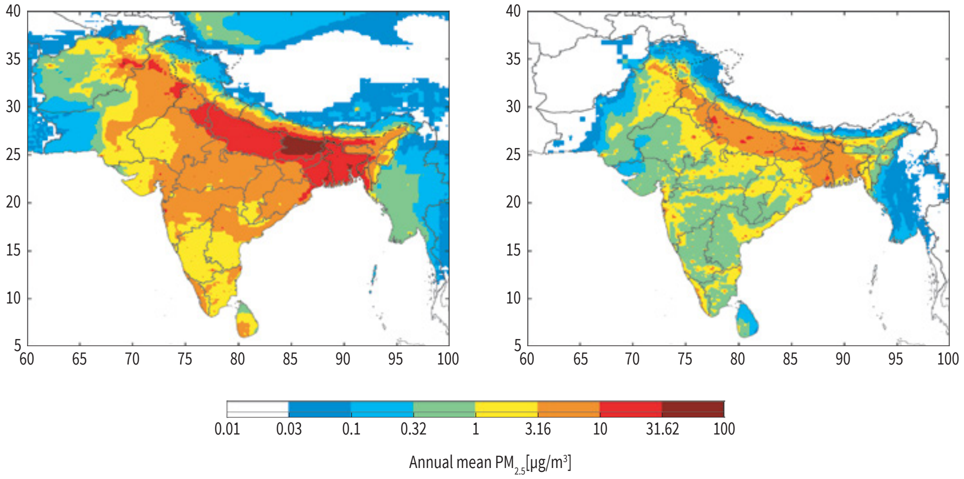
A. Power generation.

B. Large-scale industries.



C. Mobile (road and non-road) sources.

D. Small industries (including brick kilns).



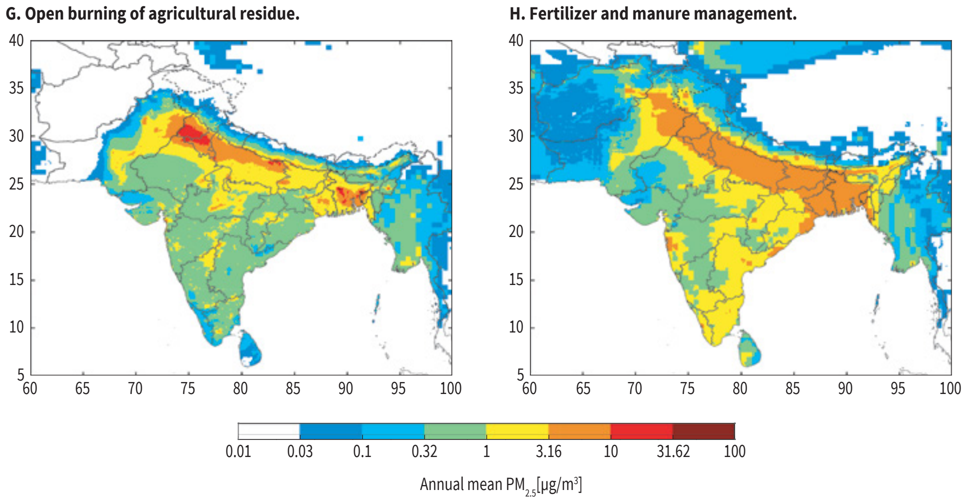
E. Residential and commercial sources.

F. Solid waste management.

Source: GAINS calculations/IIASA (2021).

Note: Fine particulate concentrations are in µg/m^3.

Figure 2.5. Concentrations of small particulate matter in ambient air originating from key emission sectors, 2018 (continuation)

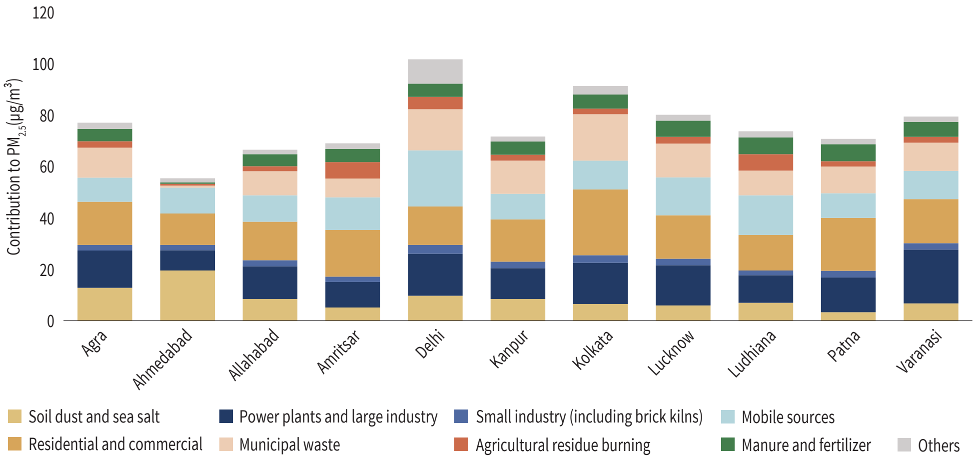


G. Open burning of agricultural residue.

H. Fertilizer and manure management.

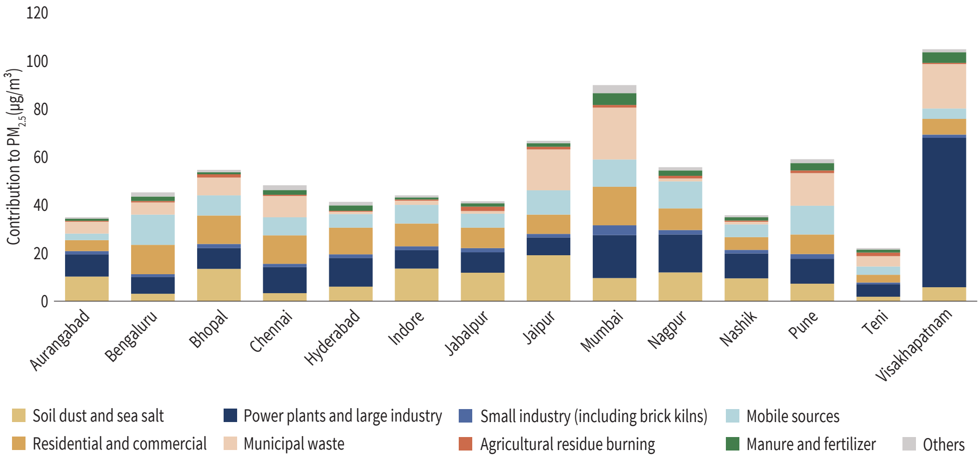
Source: GAINS calculations/IIASA (2021).
Note: Fine particulate concentrations are in μg/m³.

Figure 2.6. Contributions to population-weighted small particulate matter exposure in cities in the Indo-Gangetic Plain by source, 2018



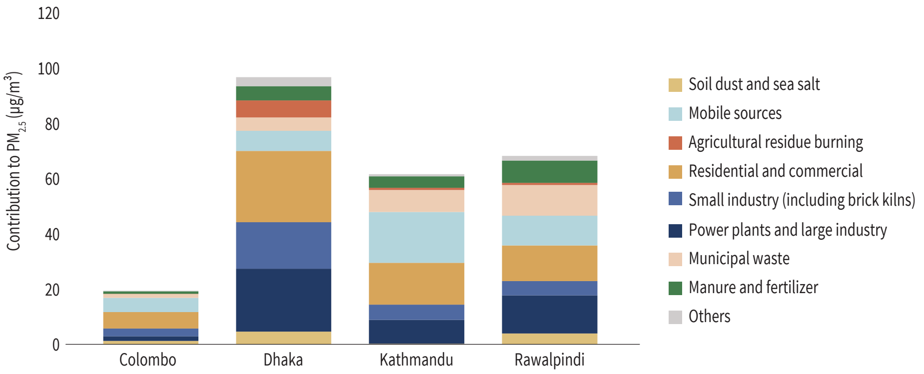
Source: GAINS calculations/IIASA (2021).
Note: Fine particulate concentrations are in μg/m³.

Figure 2.7. Contributions to population-weighted small particulate matter exposure in cities beyond the Indo-Gangetic Plain by source, 2018



Source: GAINS calculations/IIASA (2021).
Note: Fine particulate concentrations are in µg/m³.

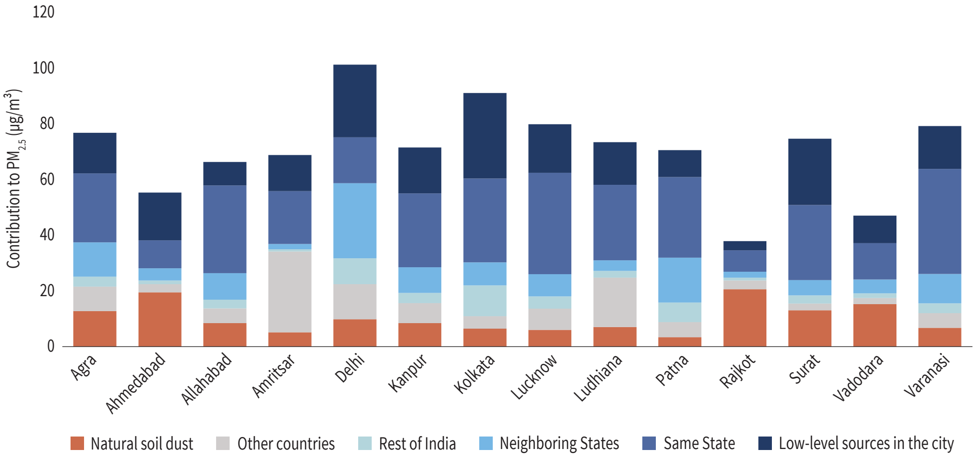
Figure 2.8. Contributions to population-weighted small particulate matter exposure in selected cities in South Asia by source, 2018



Source: GAINS calculations/IIASA (2021).
Note: Fine particulate concentrations are in µg/m3.

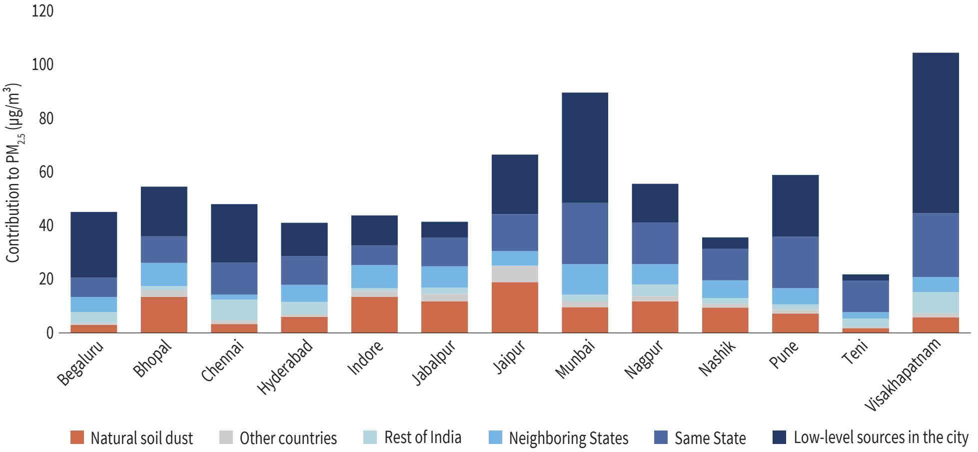
at any given location, $PM_{2.5}$ in ambient air originates from a wide range of upwind sources extending over several hundred kilometers. Conversely, emissions from any given source will be carried over similar distances and affect air quality over large downwind areas. Figures 2.9 to 2.11 reveal the origin of ambient $PM_{2.5}$ concentrations at specific locations. Especially in the Indo-Gangetic Plain, with its high large-scale emission density, only a rather small share of population-weighted $PM_{2.5}$ exposure comes from low-level sources such as road traffic,

Figure 2.9. Spatial origin of population-weighted fine particulate matter exposure in cities in the Indo-Gangetic Plain, 2018



Source: GAINS calculations/IIASA (2021).
Note: Fine particulate concentrations are in μg/m³.

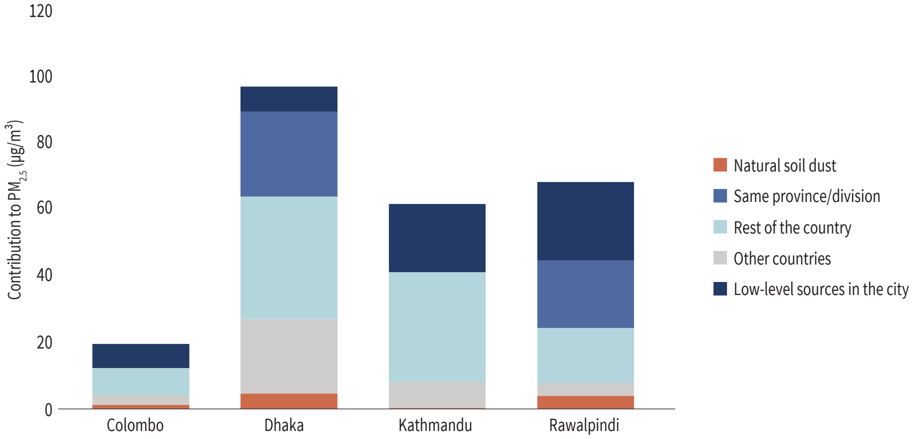
Figure 2.10. Spatial origin of population-weighted fine particulate matter exposure in Indian cities beyond the Indo-Gangetic Plain, 2018



Source: GAINS calculations/IIASA (2021).
Note: Fine particulate concentrations are in μg/m³.

the residential sector, and waste management in the same city, while the majority of $PM_{2.5}$ exposure originates from other sources in the same province/state. In other areas where outside pollution levels are generally lower, a larger share of $PM_{2.5}$ pollution in cities originates from local sources.

Figure 2.11. Spatial origin of population-weighted fine particulate matter exposure in selected cities in South Asia, 2018



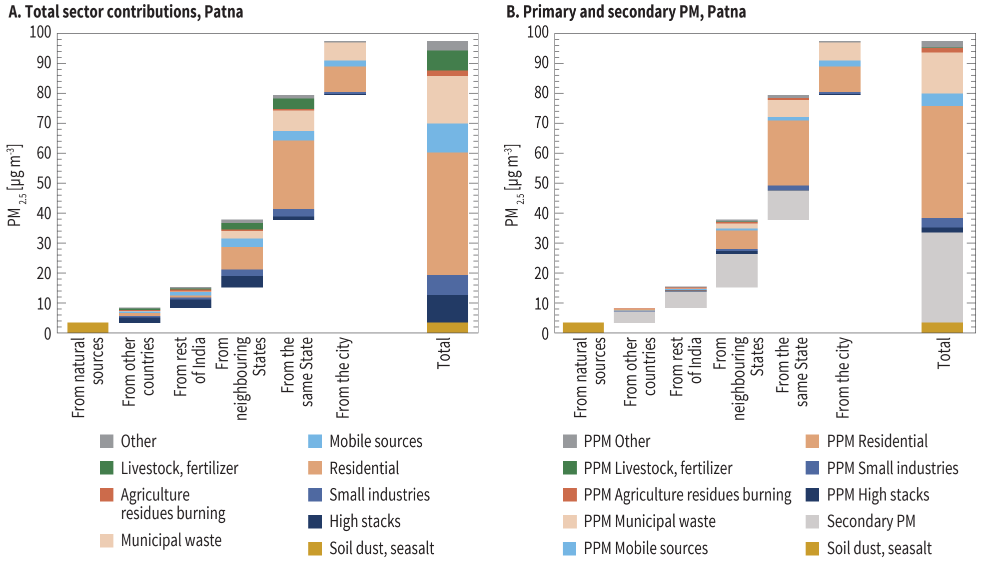
Source: GAINS calculations/IIASA (2021).
Note: Fine particulate concentrations are in µg/m³.

2.2 Implications for AQM in South Asia

Effective AQM in South Asia therefore needs to balance measures across sectors and coordinate interventions with other upwind regions. Given the variety in contributing sources, effective solutions need balanced combinations of measures across sectors and regions, and should prioritize those measures that achieve air quality improvements at relatively low cost. Support of various stakeholder groups may be facilitated by a robust and shared knowledge base on emissions sources and their consequences for air quality.

While the long-range transport of pollution requires regional coordination, effective AQM should also tailor solutions to reflect local conditions. The share of local sources in ambient $PM_{2.5}$ varies over South Asia, depending on topography, meteorology, the intensity and spatial patterns of emissions, and the size of the administrative regions. Figures 2.12 to 2.17 compare sources across the Indo-Gangetic Plain city of Patna, with Chennai, India; Dhaka, Bangladesh; Kathmandu, Nepal; Rawalpindi, Pakistan; and Colombo, Sri Lanka. As can be seen, the sources vary significantly within and across the major cities in South Asia.

Figure 2.12. Source allocations of population exposure to total fine particulate matter and primary versus secondary fine particulate matter in Patna, Bihar State, India, 2018

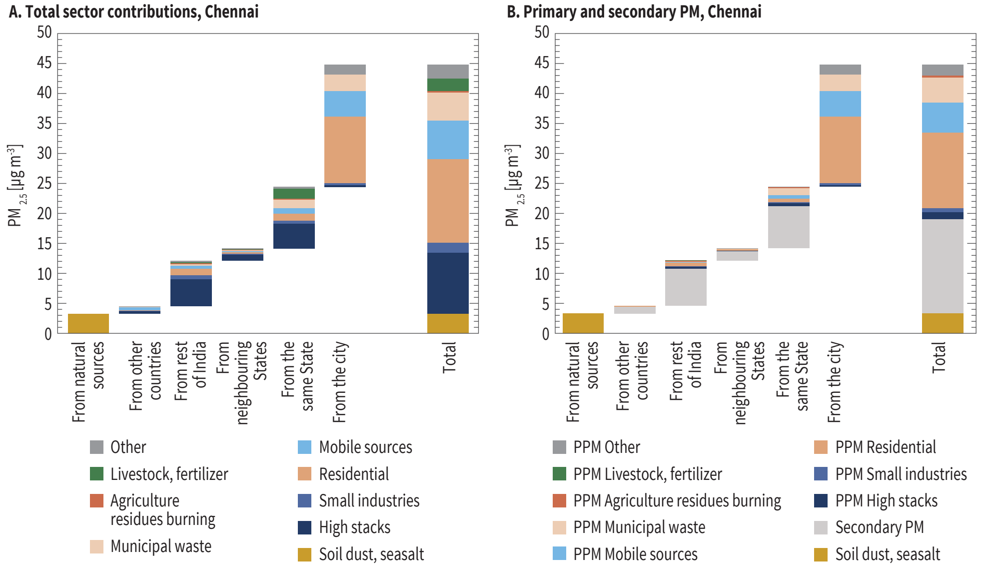


A. Total sector contributions, Patna

B. Primary and secondary PM, Patna

Source: GAINS calculations/IIASA (2021).
Note: Fine particulate concentrations are in µg/m^3.

Figure 2.13. Source allocations of population exposure to total fine particulate matter and primary versus secondary fine particulate matter in Chennai, Tamil Nadu State, India, 2018

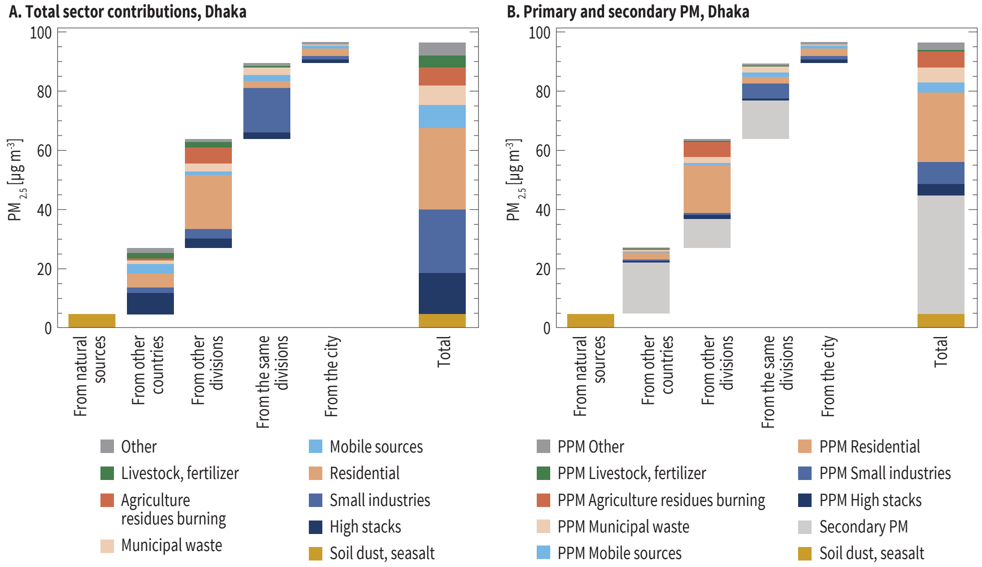


A. Total sector contributions, Chennai

B. Primary and secondary PM, Chennai

Source: GAINS calculations/IIASA (2021).
Note: Fine particulate concentrations are in µg/m^3.

Figure 2.14. Source allocations of population exposure to total fine particulate matter and primary versus secondary fine particulate matter in Dhaka, Bangladesh, 2018

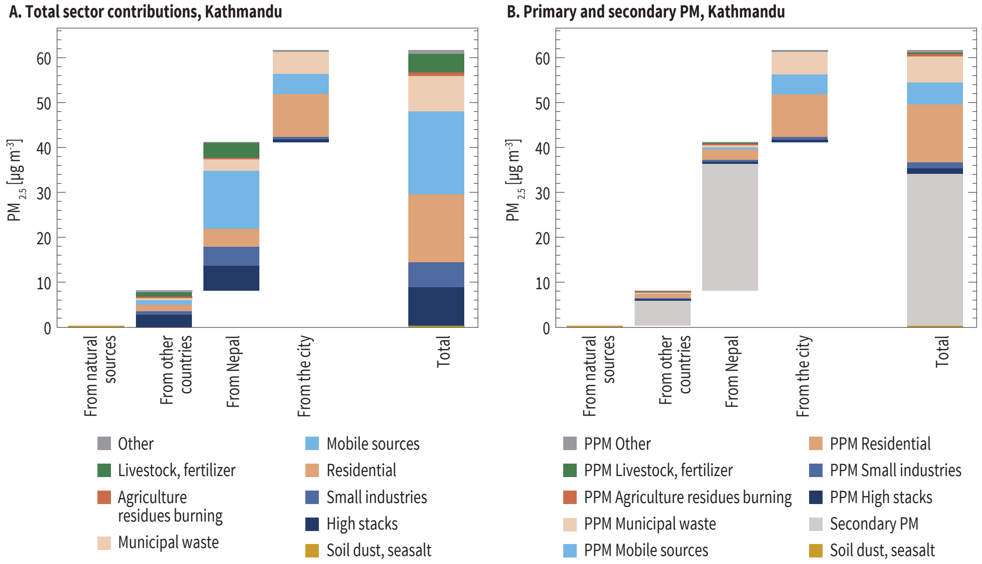


A. Total sector contributions, Dhaka

B. Primary and secondary PM, Dhaka

Source: GAINS calculations/IIASA (2021).
Note: Fine particulate concentrations are in µg/m³.

Figure 2.15. Source allocations of population exposure to total fine particulate matter and primary versus secondary fine particulate matter in Kathmandu, Nepal, 2018

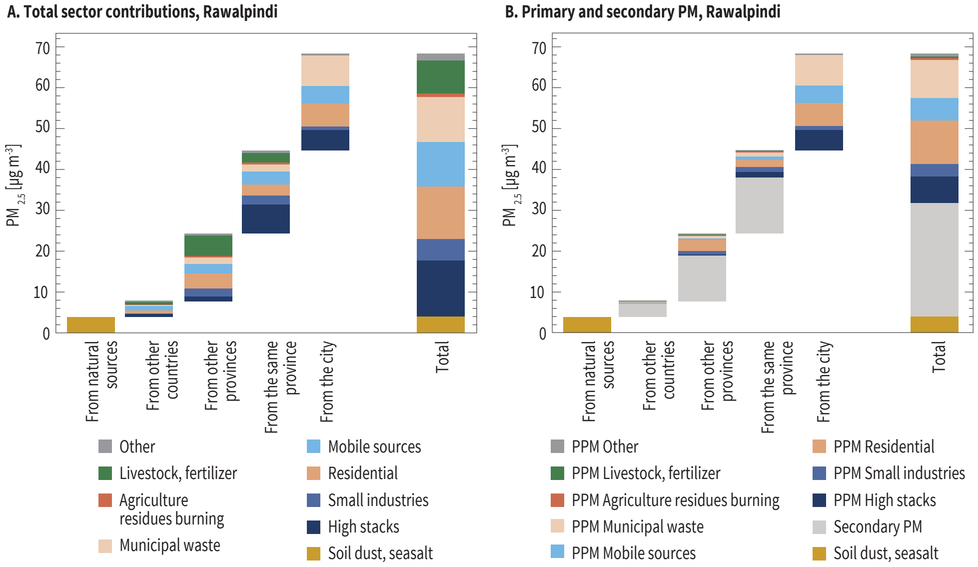


A. Total sector contributions, Kathmandu

B. Primary and secondary PM, Kathmandu

Source: GAINS calculations/IIASA (2021).
Note: Fine particulate concentrations are in µg/m³.

Figure 2.16. Source allocations of population exposure to total fine particulate matter and primary versus secondary fine particulate matter in Rawalpindi, Pakistan, 2018

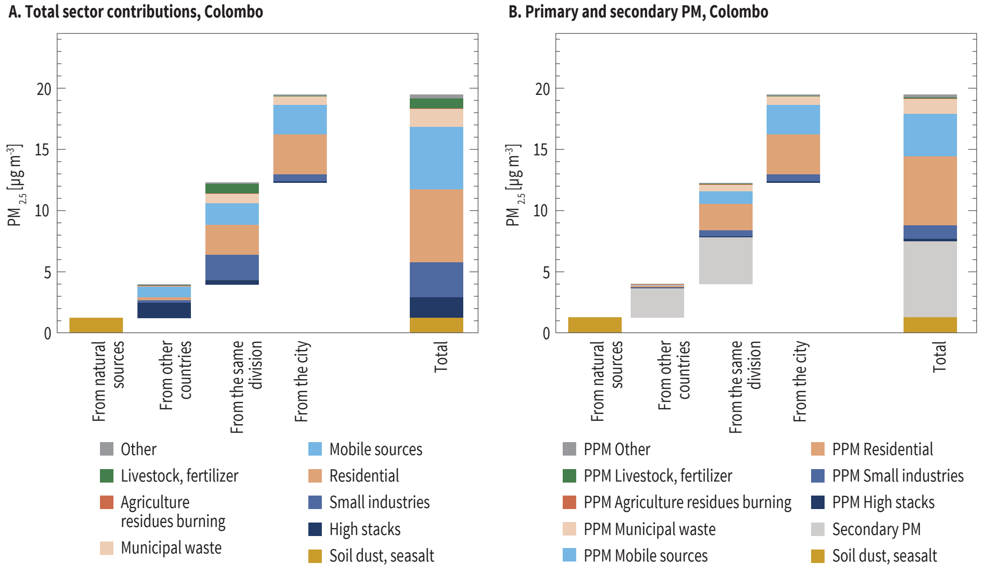


A. Total sector contributions, Rawalpindi

B. Primary and secondary PM, Rawalpindi

Source: GAINS calculations/IIASA (2021).
Note: Fine particulate concentrations are in μg/m³.

Figure 2.17. Source allocations of population exposure to total fine particulate matter and primary versus secondary fine particulate matter in Colombo, Sri Lanka, 2018



A. Total sector contributions, Colombo

B. Primary and secondary PM, Colombo

Source: GAINS calculations/IIASA (2021).
Note: Fine particulate concentrations are in μg/m³.

2.3 The importance of airshed management for South Asia

The strong spatial interconnections between emissions sources in the South Asia region limit the ability of single cities, states, and provinces to achieve steep reductions in pollution concentrations on their own, even if they could eliminate all emissions within their own territory. This situation is not, however, unique to South Asia. Useful approaches have been developed in other parts of the world to coordinate AQM among different jurisdictions. *In particular,* the airshed concept *emphasizes the common responsibility for a shared resource, i.e., the air mass in each region, and facilitates coordinated but differentiated response strategies that achieve effective air quality improvements, while respecting the heterogeneity in the ability of different regions to act.*

An airshed can be defined as a region that shares a common flow of air, which may become uniformly polluted and stagnant. Air quality within an airshed will largely depend on pollution sources within it. The extension of an airshed is strongly determined by the spatial distribution and intensities of emissions sources, as well as the typical patterns of pollution transport in the atmosphere, which depends on local geography, meteorology, and climatic conditions.

As the formation of secondary particles and the transport of primary and secondary particles take place over large geographic areas, airsheds can extend over several hundred kilometers, well beyond the boundaries of cities.

The need for airshed-wide coordination emerges particularly for the urban areas of South Asia, in which a high share of $PM_{2.5}$ pollution in ambient air is imported from outside the area. In most cases, cities alone cannot achieve steep reductions in pollution on their own, even if they could eliminate all emissions within their own territory.[2] Given the prevailing high concentrations in many urban agglomerations in South Asia, coordination between administrative regions that constitute common airsheds, especially between cities and the surrounding states or provinces, will be indispensable in moving toward the WHO Interim Targets, and especially for doing so in a cost-effective manner.

To explore potential candidate airsheds in South Asia, this study applied a two-step approach that considers the following physical features (note that political considerations are not addressed here):

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[2] However, the specific conditions in several areas of South Asia call for airshed management approaches that include multiple states, provinces and even countries. The delineation of airsheds must include many factors, including physical geography, as well as economic and political considerations, and their definition inevitably involves subjective judgements.

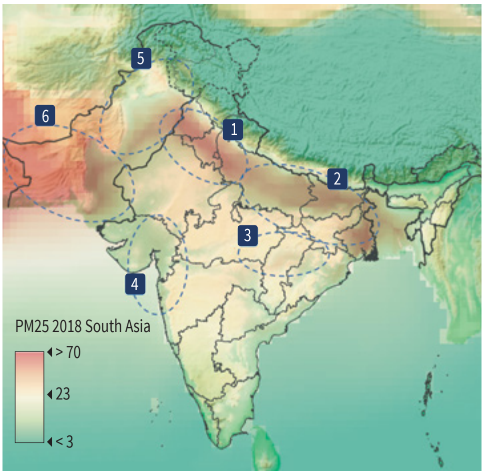
i) Overlay pollution concentration maps[3]—yearly $PM_{2.5}$ concentrations in 10 x 10-kilometer grid cells—over elevation maps to define where concentrations are trapped within the topography.

ii) Determine $PM_{2.5}$ transportation patterns between source regions within the airshed compared with $PM_{2.5}$ transportation patterns inside and outside the airshed.

This approach revealed six priority regions (Figure 2.18):

1. West/Central Indo-Gangetic Plain: Punjab (Pakistan), Punjab (India), Haryana, part of Rajasthan, Chandigarh, Delhi, Uttar Pradesh.
2. Central/Eastern Indo-Gangetic Plain: Bihar, West Bengal, Jharkhand, Bangladesh.
3. Middle India: Odisha/Chhattisgarh.
4. Middle India: eastern Gujarat/western Maharashtra.
5. Northern/central Indus River Plain: Pakistan, part of Afghanistan.
6. Southern Indus Plain and further west: South Pakistan, Western Afghanistan extending into Eastern Iran.

Figure 2.18. Six illustrative airsheds in South Asia based on fine particle concentrations, topography, and fine particle transportation between source regions



Source: Overlay by the World Bank project team and IIASA.
Note: Fine particulate concentrations are in µg/m^3.

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[3] $PM_{2.5}$ concentration maps were generated from GAINS by International Institute for Applied Systems Analysis (IIASA) while topographic maps were made by the World Bank. The map overlay was made by World Bank project team.

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Annex A.2.1. Application of GAINS modeling in South Asia

To capture the diversity across South Asia, the GAINS model implementation for this study distinguished 31 emission source regions, individual states and provinces of large countries. The impacts of their emissions on regional air quality were computed for more than 500 individual cities, as well as for rural areas at a spatial resolution of about 50 x 50 kilometers (0.5 x 0.5 degrees).

While air pollution has a wide range of negative impacts on human health, agricultural crops and natural ecosystems, this analysis focuses on the most harmful pollutant to human health, $PM_{2.5}$. It does not assess additional threats to human health and vegetation caused by ground-level ozone, to biodiversity due to excess nitrogen deposition, or damage to sensitive terrestrial and aquatic ecosystems caused by acid deposition.

Any effective clean air strategy will vary in approach based on the context of each country and/or city, as well as its capacity to develop and implement measures. There is no uniform policy prescription for air quality that is applicable to all countries and regions; such an approach would neither be possible nor desirable for a problem that is so diverse in local circumstances.

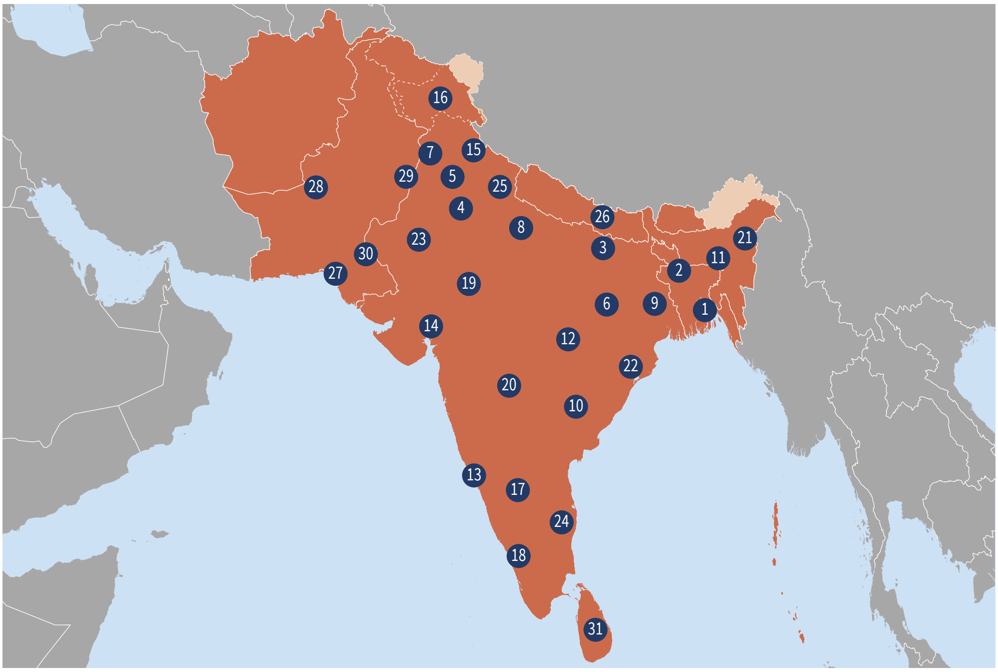
The modeling studies reported in the report were conducted using data on economic activities, emissions, and ambient concentrations of the relevant pollutants in Bangladesh, India, Nepal, Pakistan, and Sri Lanka. For Bangladesh, India, and Pakistan, the analysis focused on 29 sub-national regions, covering individual states/divisions and/or aggregates of these. These sub-regions are used for scientific convenience only and have no official or administrative significance.

The analysis presented in this report attributes changes in air quality to sources both within and outside each of the 31 study regions. The regions are used for scientific convenience only but, by studying which regions are affected by others, it is possible to suggest which regions would benefit most from cooperation. Thus, the regions may be considered the building blocks for potential airsheds, which may be made up of two or more of the study regions.

This report developed a preliminary methodology for delineating airsheds in South Asia, which required taking many factors into account, including physical geography together with economic and political considerations, and involved developing both pollution concentration maps and $PM_{2.5}$ transportation patterns.

The analysis for South Asia is fed by numerous local data sources, supplemented by relevant international information that has been obtained under comparable conditions. To capture the specific characteristics of the region, the implementation of the GAINS framework for

Figure A.2.1. The 31 emission source regions used for modeling purposes in this analysis



No.	Country	Sub-region distinguished in the analysis
1	Bangladesh	Dhaka
2		Rest of Bangladesh
10	India	Andhra Pradesh
11		Assam
9		West Bengal
3		Bihar
12		Chhattisgarh
4		Delhi National Capital Territory
21		North East (excluding Assam)
13		Goa
14		Gujarat
5		Haryana
15		Himachal Pradesh

No.	Country	Sub-region distinguished in the analysis
6		Jharkhand
17		Karnataka
18		Kerala
20		Maharashtra-Dadra-Nagar, Haveli-Daman-Diu
19		Madhya Pradesh
22		Orissa
7		Punjab (India)
23		Rajasthan
24		Tamil Nadu
25		Uttaranchal
8		Uttar Pradesh
16		Union Territories of Jammu and Kashmir
26	Nepal	Whole country
27	Pakistan	Karachi
28		North-West Frontier Province and Baluchistan
29		Punjab (Pakistan)
30		Sindh
31	Sri Lanka	Whole country

South Asia drew on a wide range of national data, including, among others, published statistics on socio-economic aspects, fuel consumption, industrial and agricultural activities, and the transport and waste management sectors.

This report developed coherent emission inventories for all precursor emissions of $PM_{2.5}$ in South Asia. For each of the 31 regions, the study compiled emission inventories of the relevant air pollutants, primary $PM_{2.5}$, SO_2, NO_x, NH_3, NMVOCs and short-lived climate pollutants (SLCPs). Estimates were developed for 2015 and 2018, considering the effectiveness of applied emission control measures. Priority was given to local measurements, and data gaps filled by information from international studies that have been conducted for similar socio-economic and technological conditions.

The spatial patterns of $PM_{2.5}$ and its precursor emissions were estimated at a $0.5^0 \times 0.5^0$ longitude–latitude resolution, based on relevant proxy variables updated from Klimont et al. (2017). These estimates rely on the most recent updates of data on plant locations, remote sensing of open biomass burning, and waste statistics that were originally developed within the Global Energy Assessment project (GEA 2012). For the residential and transport sectors, finer resolved emission distribution maps have been developed at a 10 x 10-kilometer resolution, employing fine-scale gridded population data and road maps. Natural emissions are based on estimates employed by the European Monitoring and Evaluation Programme (EMEP) (Simpson et al. 2012) and GEOS-Chem (van Donkelaar et al. 2019) atmospheric chemistry and transport models.

Air quality is assessed over all South Asia at a spatial resolution of 10 x 10 kilometers and compared against available monitoring data. The fine-scale emission inventory serves as an input for the calculation of $PM_{2.5}$ concentrations in ambient air across South Asia. Using the well-established EMEP atmospheric chemistry-transport model (Simpson et al. 2012), total annual mean concentrations of $PM_{2.5}$ are computed for the 200 largest cities, while concentrations in rural areas are estimated at a 10 x 10-kilometer resolution. These calculations combine the fine-scale dispersion characteristics of primary $PM_{2.5}$ emissions, which lead to steep gradients around emission sources, with the formation of secondary particles and the long-range transport of $PM_{2.5}$ in the atmosphere. These are computed at a 0.5^0 x 0.5^0 longitude–latitude, about 50 x 50-kilometer resolution. Calculations were conducted at hourly intervals for meteorological datasets for 2015 and 2018.

After validation of the computed concentrations against available observations, the dispersion model has been used to distill the spatial dispersion pattern of low- and high-level emission sources of primary $PM_{2.5}$, SO_2, NO_x, NH_3 and NMVOC for each South Asian emissions source region. Assuming constant meteorological conditions of 2018, these source-receptor relationships were then used for estimating concentration fields for different emission patterns, for example, those resulting from the application of emission controls in the future.

While public attention and legislative AQM focuses on episodic concentration peaks at pollution hotspots, maximizing public health benefits is better informed through a focus on population exposure. In many cases, public attention on air pollution focuses on the most polluted places, comparing measured concentrations against national ambient air quality standards. This aligns with the prevailing legal frameworks for AQM, which prescribes compliance with national ambient air quality standards throughout the entire territory, and thereby in the most polluted places. Observed concentrations peaks, for example, at curb sides in busy streets, are however not necessarily the best metric for protecting public health, as they are only loosely related to long-term exposure of the entire population, which has been identified as the most powerful predictor for the adverse health impacts from air pollution.

CHAPTER 3

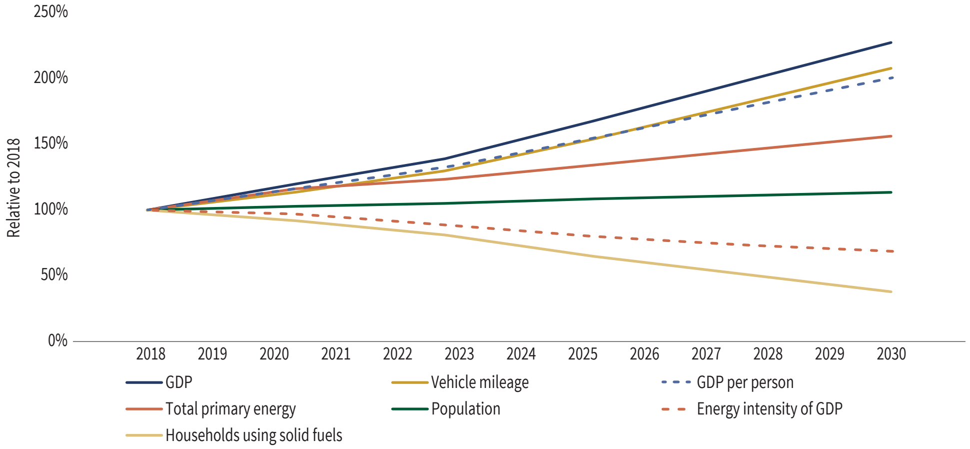
Cost-effective Measures to Deal with Ambient Air Pollution in South Asia

The cost-effectiveness of alternative approaches for further air quality improvements varies, and the most cost-effective scenarios are those that explicitly consider trans-boundary pollution. This chapter considers four pollution control scenarios that differ based on the levels of ambition, the rationale for prioritizing efforts, and the degree of coordination across jurisdictions. These four scenarios, described in detail below, range from scenarios that only upscale current efforts to the maximum technically feasible measures for reducing air pollution.

As a starting point, a baseline projection for 2030 is first developed, revealing the pivotal importance of the full implementation and enforcement of recently adopted air quality legislation. Many factors besides legislation will change the relative contribution of the various economic sectors on emissions, including new technology, population growth, growing urbanization, and economic development. This baseline projection assumes continued population and economic growth, with a doubling of per-person income by 2030. Economic structural changes and programs for enhanced energy efficiency will reduce the energy intensity of GDP, such that total primary energy consumption will grow less than total GDP. Reduced poverty and recent policies on access to clean fuels will reduce the number of households using solid biomass by 60 percent. In contrast, vehicle kilometrage closely follows the income trend (Figure 3.1).

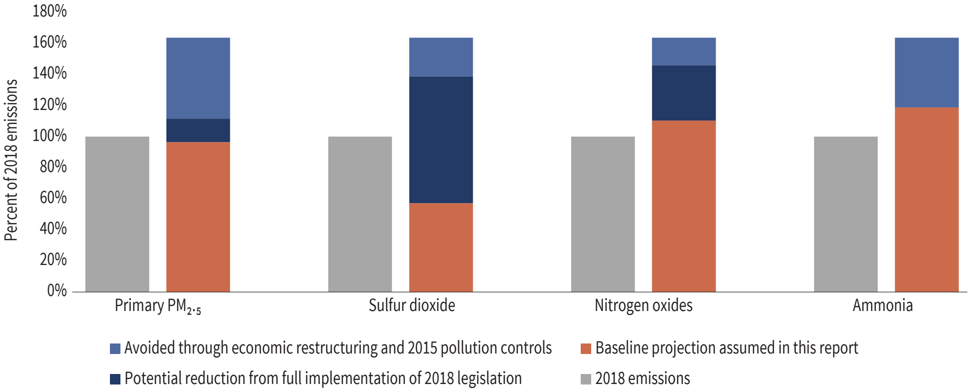
Air quality policies and measures adopted by South Asian governments so far will help decouple emission trends from GDP growth, but the extent will depend on enforcement of this recent legislation. Compared with the assumed rise in GDP by 2030, the already implemented emission controls, together with structural economic changes and energy policies, will moderate further growth of $PM_{2.5}$ precursor emissions. Since 2015, governments have introduced additional legislation, but it is yet to be fully implemented. If fully implemented and effectively enforced, these new measures would deliver much lower emissions: primary $PM_{2.5}$ would decline by 4 percent rather than grow by 12 percent; SO_2 would decline by 43

Figure 3.1. Indicator trends for population, economic development and energy use assumed in the baseline scenario in South Asia region, 2018–2030



Source: GAINS/IIASA (2021).
Note: Trends are expressed as indices with 2018 as baseline (index in 2018 = 100).

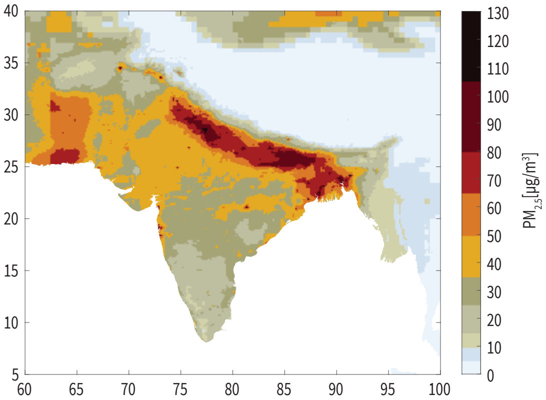
Figure 3.2. Changes in fine particulate matter, precursor emissions in South Asia between 2018 and 2030, and the key factors leading to decoupling from GDP growth, 2018–2030



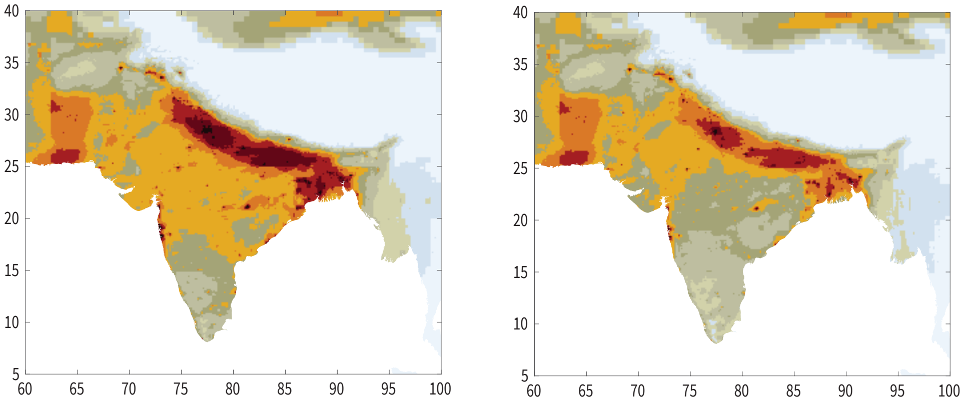
Source: GAINS calculations/IIASA (2021).
Note: Changes are expressed in percentage. Emissions would increase by 160 percent absent of interventions. The light blue bars represent the avoided exposure in 2030 resulting from implementation of the 2015 legislation package. The darker blue bars show additional reductions in exposure that could be achieved by the full and efficient implementation of the additional policies and measures of the 2018 package. The orange bars show the expected 2030 emissions with the implementation of the 2015 and 2018 legislation.

percent instead of increasing by 39 percent; and growth in NO_x would decline from 46 to 10 percent. However, NH_3 emissions would not be affected as there is no relevant legislation (Figure 3.2). The large difference between the 2015 and 2018 legislation cases highlights the importance of strict enforcement of current policies and measures, and illustrates the potential gains from the effective implementation of the recent legislation.

Figure 3.3. South Asia's ambient concentrations of fine particulate matter in 2018 and in 2030 with the already implemented emission controls and with full implementation of measures that were decided between 2015 and 2018



A. Ambient concentrations of fine particulate matter in 2018



B. Ambient concentrations of fine particulate matter in 2030 with the already implemented measures

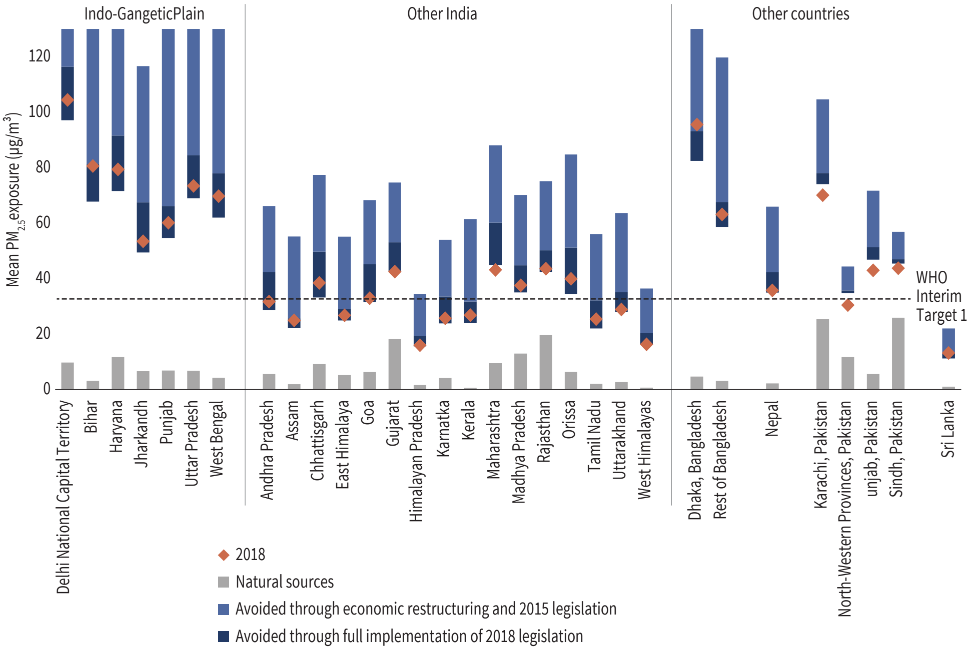
C. Ambient concentrations of fine particulate matter in 2030 with the measures decided in 2015-2018

Source: GAINS calculations/IIASA (2021).
Note: Fine particulate concentrations are in μg/m³.

These policies and measures will not, however, be sufficient to reduce $PM_{2.5}$ concentrations throughout the region to meet the WHO Interim Target 1 of 35 μg/m³ in large parts of South Asia (Figure 3.3). The effective enforcement of recent pollution control legislation will affect the margin of uncertainty around future air quality. Not only could the recently adopted legislation compensate for increased emissions from the steep increase in economic activity that is projected, but it could also deliver effective reductions in ambient $PM_{2.5}$ concentrations in many areas.

The envisaged structural changes in the economy, together with the already implemented emission controls, will avoid a significant deterioration from current levels. Whether they

Figure 3.4. Modeled mean population exposure to fine particulate matter in selected regions in 2018 and 2030



Source: GAINS calculations/IIASA (2021).
Note: The light blue bars represent the avoided exposure in 2030 resulting from implementation of the 2015 legislation package. The darker blue bars show additional reductions in exposure that could be achieved by the full and efficient implementation of the additional policies and measures of the 2018 package. The orange dots denote the mean population exposure in 2018 and the gray bars show the contribution from natural sources—soil dust and sea salt. Fine particulate concentrations are in µg/m³.

will reduce current population exposure (the orange dots in Figure 3.4), however, depends on the effectiveness of implementation (the dark blue bars). Thus, in areas with high concentrations of $PM_{2.5}$ today, such as the Indo-Gangetic Plain and in urban agglomerations in other regions, mean population exposure will remain far above the WHO Interim Target 1, 35 µg/m^3, and even with the introduction of the latest measures, about two-thirds of the population in South Asia will remain exposed to $PM_{2.5}$ concentrations above this target level.

3.1 Four AQM approaches that go above and beyond the current policies

Given the limited air quality improvements that can be expected from the recent legislation, additional air quality measures and cost implications are examined for four alternative approaches to AQM in South Asia.

1. An ‘***Ad-hoc* selection of measures scenario**’ assesses an upscaling of the measures that are currently in place in parts of South Asia to the whole region. Following current

widespread thinking in the region, the main focus is on the power sector, large-scale industry, and road transport. Cost-effectiveness receives less attention and measures are often decided regardless of air quality interactions from other territories.

2. A '**Maximum technically feasible emissions reduction scenario**' explores the range of air quality improvements that could be achieved by 2030 from the full implementation of all technical emission controls that are currently available on the world market—irrespective of cost. New technologies are introduced only through new investment, with no allowances made for premature scrapping of existing capital stock.

3. The '**Compliance with WHO Interim Target 1 scenario**' provides a more targeted approach; AQM focuses on **pollution hotspots** in South Asia and brings mean population exposure to $PM_{2.5}$ in each region into compliance with the WHO Interim Target 1 of 35 $\mu g/m^3$. Addressing the long-range transport of pollution to the most-polluted areas requires regional coordination, whereas measures in other regions are selected based on their cost-effectiveness.

4. The '**Toward the next lower WHO Interim Target scenario**' seeks cost-effective cuts in harmful population exposure to $PM_{2.5}$ through a common but differentiated approach that is coordinated across South Asia. With a long-term aim of moving toward the next lower WHO Interim Target for $PM_{2.5}$, measures are selected such that, by 2030, the present difference in mean population exposure to the next lower WHO Interim Target level in each region falls by 90 percent.[4] Measures are chosen based on their cost-effectiveness and, where necessary, coordinated with neighboring regions.

Beyond the 2018 air quality legislation, the scenarios outline the significant scope for further air quality improvements that could be achieved through additional measures. By 2030, the implementation of the 'Maximum technically feasible emissions reductions scenario' throughout South Asia could bring mean population exposures to $PM_{2.5}$ in each region distinguished in this analysis below the WHO Interim Target 1. This is indicated by the dark and light-yellow bars in Figure 3.5, starting from the exposure levels that emerge from compliance with the 2018 legislation. In this case, average population exposure in South Asia could be reduced by about two-thirds from about 50 $\mu g/m^3$ in 2018 to 17 $\mu g/m^3$ in 2030. Residual exposure originates from natural sources (the gray bars in Figure 3.5) and from emissions that cannot be removed by currently available technical measures. Importantly,

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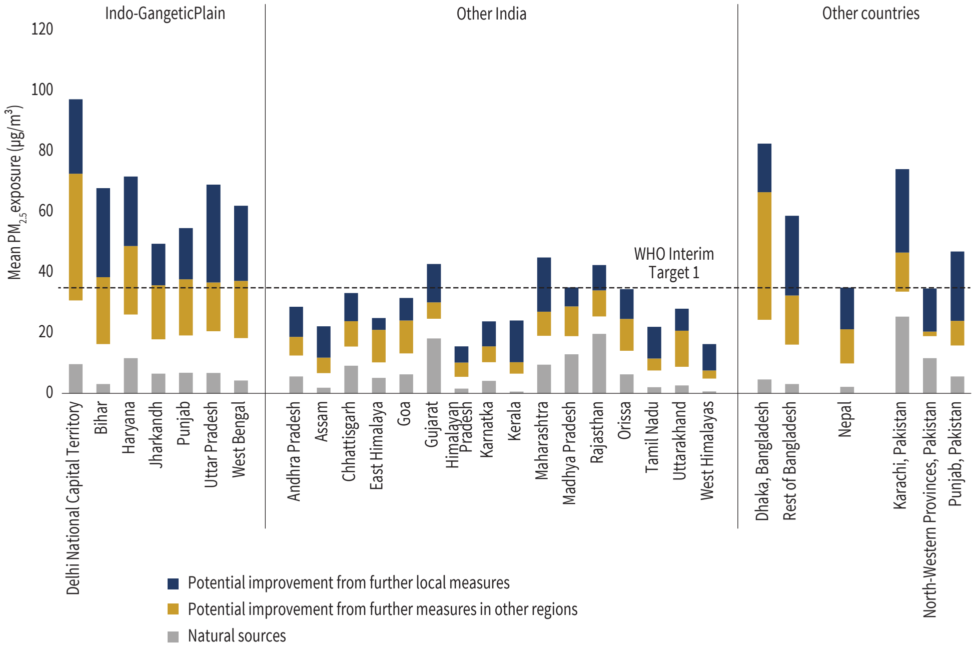
[4] The WHO Air Quality Guideline for mean annual concentrations of $PM_{2.5}$ is 5 $\mu g/m^3$. The WHO has established four Interim Targets toward the achievement of the Guideline – Interim Target 1, 35 $\mu g/m^3$; Interim Target 2, 25 $\mu g/m^3$; Interim Target 3, 15 $\mu g/m^3$, Interim Target 4, 10 $\mu g/m^3$ (WHO). The 90 percent reduction would allow different regions to move toward different Interim Targets, depending on their 2018 pollution level.

Table 3.1. Four modeled approaches to AQM in South Asia

Scenario 1: Ad-hoc selection of measures	Scenario 2: Maximum technically feasible emissions reductions
• Scaling-up of measures that are currently taken in parts of South Asia to all its regions • Each region acts independently	• Full implementation of all technical emission controls that are available on the world market • No regional coordination
Scenario 3: Compliance with WHO Interim Target 1 everywhere in South Asia	**Scenario 4: Toward the next lower WHO Interim Target**
• In all regions, mean population exposure is reduced to 35 μg/m^3 • Regions cooperate to the extent they are contributing to pollution hotspots	• Reduce the present difference of PM$_{2.5}$ exposure by 90% to the next lower WHO Interim Target in each region • Full coordination across regions to maximize cost-effectiveness

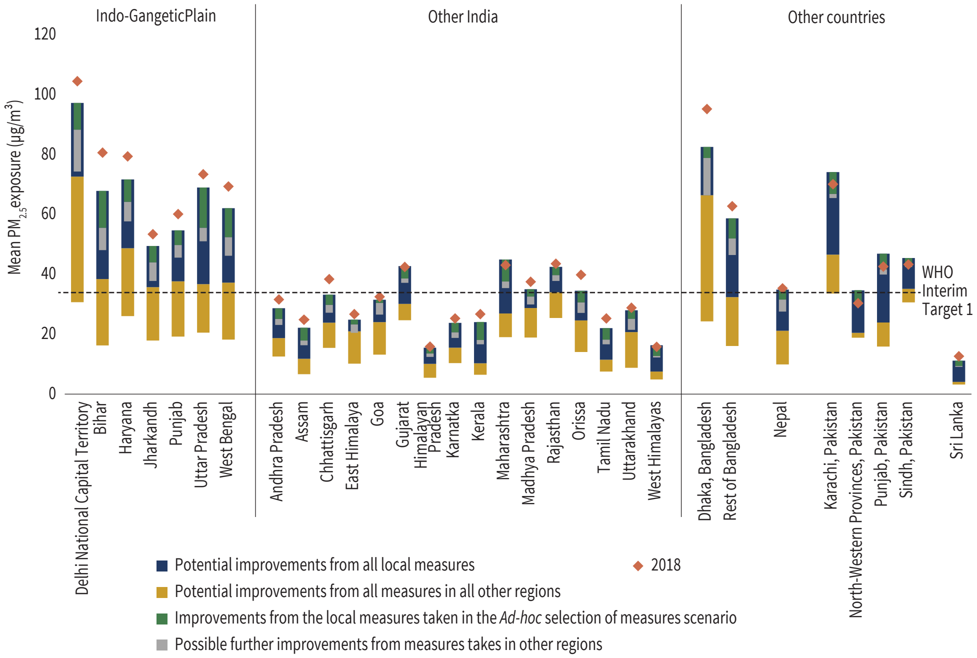
Figure 3.5. Modeled potential improvements in population exposure to fine particulate matter due to the full implementation of the 'Maximum technically feasible emissions reductions scenario' in the analyzed regions in 2030



Source: GAINS calculations/IIASA (2021).
Note: Fine particulate concentrations are in μg/m^3.

several regions, especially in the Indo-Gangetic Plain and urban agglomerations, cannot achieve the WHO Interim Target 1 on their own even if they implemented all technically

Figure 3.6. Improvements in exposure to fine particulate matter from the measures taken in the '*Ad-hoc* selection of measures scenario' in 2030



Source: GAINS calculations/IIASA (2021).
Note: Fine particulate concentrations are in µg/m³.

feasible measures (indicated by the blue bars), as the inflow of pollution from outside regions and from natural sources already exceeds 35 µg/m^3.

Without coordination, regions cannot reliably predict their future air quality. The long-range transport of pollution makes actual air quality improvements in a region dependent not only on local measures but also on measures taken in other areas. This is illustrated in Figure 3.6, in which the black bars indicate, for 2030, exposure reductions from the measures taken in the '*Ad-hoc* selection of measures scenario' within the same region. Obviously, benefits from the local measures account for only a minor share of the full potential and miss the WHO Interim Target 1 by a wide margin in many regions. At the same time, however, regions will enjoy the spillover benefits from measures taken beyond their borders (the gray bars in Figure 3.6), but the extent of these would, without regional coordination, remain unknown.[5]

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[5] Starting from the exposure following compliance with 2018 legislation (Figure 3.4), the dark yellow bars indicate further possible improvements from the implementation of all measures that could be taken within a region. The light-yellow bars show additional improvements that could result from measures taken in other regions. Red dots show exposure in 2018. The black bars show improvements in exposure to fine particulate matter from the measures taken in the '*Ad-hoc* selection of measures scenario' within the region, while the gray bars show possible further improvements from measures taken in other regions.

Airshed-wide coordination of measures enhances the effectiveness of AQM strategies. A lack of knowledge of the spillover impacts from measures in other regions within the same airshed will inevitably lead to costly AQM solutions, as it prohibits the selection of the most efficient measures to meet given air quality targets. Airshed-wide coordination, despite its governance challenges, has proven to be a powerful mechanism in other regions of the world (California [the United States], European Union, and Jing-Jin-Ji Region [China]) for enhancing the economic efficiency of effort spent on AQM.

Two of the above scenarios—'Compliance with WHO Interim Target 1 scenario' and 'Toward the next lower WHO Interim Target scenario'—**illustrate the power of coordinated approaches**. In both cases, regions would cooperate to the extent necessary for achieving common air quality improvement targets through differentiated action such that, overall, the economic resources spent on pollution controls are minimized.

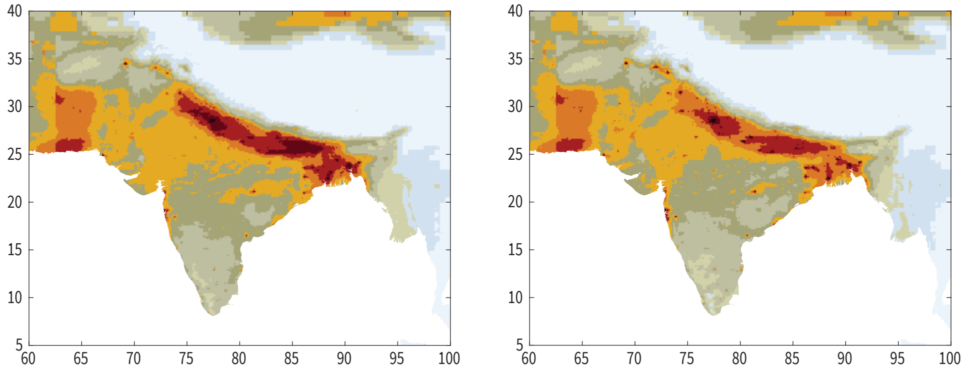
The two scenarios aim at different air quality targets, and result in different distributions of air quality benefits and costs.

- Following conventional approaches, the 'Compliance with WHO Interim Target 1 scenario' prioritizes action in the most-polluted places by imposing a uniform target that should be met in all regions of South Asia. For convenience, the WHO Interim Target 1 of 35 μg/m^3 has been adopted for 2030. The ambient PM$_{2.5}$ levels under this scenario are often lower than under the 'Toward the next lower WHO Interim Target scenario', especially in the Indo-Gangetic Plain.
- In the 'Toward the next lower WHO Interim Target scenario' all regions reduce their mean exposure levels gradually along the four WHO Interim Targets of 35, 25, 15, and 10 μg/m^3 toward the WHO Guideline of 5 μg/m^3. This more innovative approach does not delay progress that could easily be made in less-polluted places until the air quality target becomes achievable in the more-polluted places. Most importantly, a more uniform distribution of air quality improvements delivers significantly higher health benefits to societies, while harvesting gains from low-cost measures.

Due to their contrasting target-setting rationales, the four scenarios result in a rather different distribution of air quality improvements (Figure 3.7). Most notably, in 2030, the WHO Interim Target 1 appears achievable throughout South Asia except in areas with high levels of pollution from natural sources. Local hotspots with exposures above 35 μg/m^3 remain in the scenarios, even if the mean exposure in the region falls below this level.

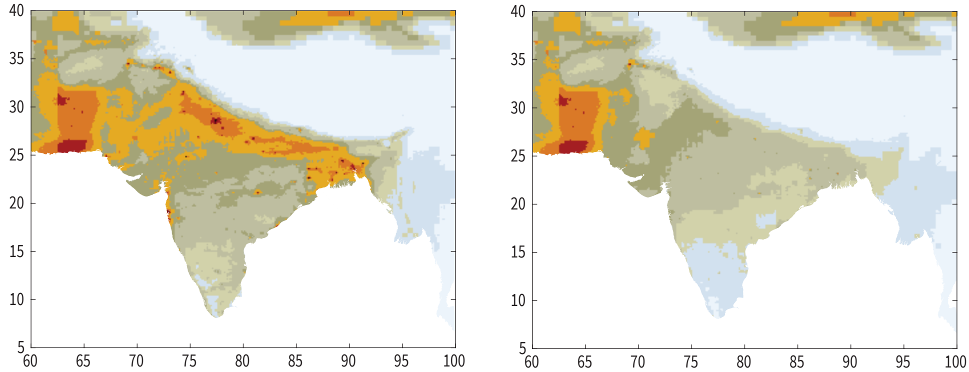
The four AQM approaches differ not only in the amount and regional distribution of improvements, but also in their cost-effectiveness.

Figure 3.7. Ambient concentrations of fine particulate matter in 2018 and the scenarios for 2030



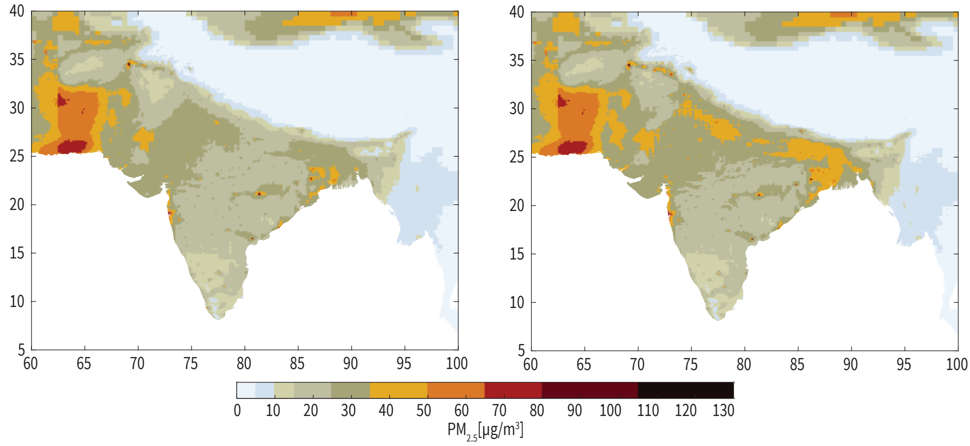
A. 2018

B. 2030 with 2018 legislation



C. 'Ad-hoc selection of measures scenario' in 2030

D. 'Maximum technically feasible emissions reductions scenario' in 2030



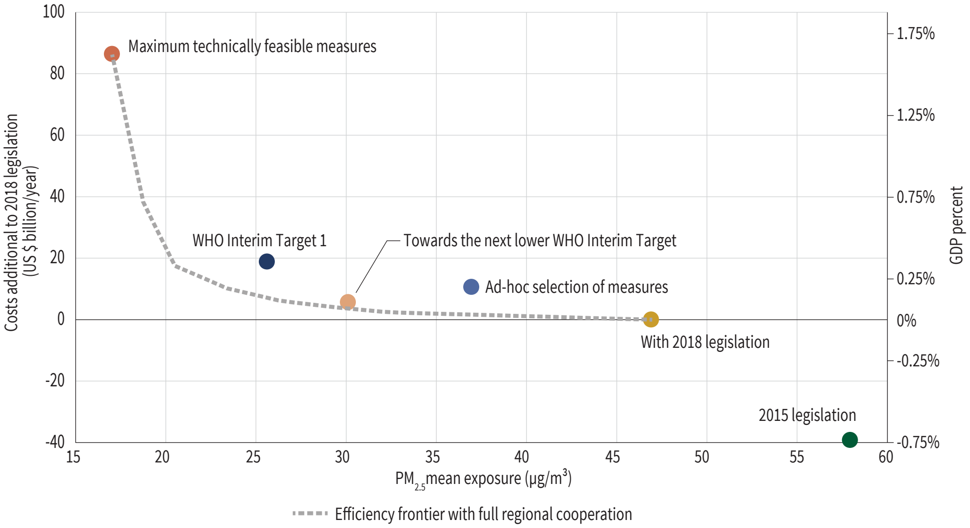
E. Compliance with WHO Interim Target 1 scenario' everywhere in South Asia, 2030

F. 'Toward the next lower WHO Interim Target scenario' in 2030

Source: GAINS calculations/IIASA (2021).

Note: Fine particulate concentrations are in µg/m^3.

Figure 3.8. Exposure reductions and costs of associated emission controls for the four modeled scenarios in South Asia region in 2030



Source: GAINS calculations/IIASA (2021).
Note: Costs are in US$ billion per year and percent GDP.

- As a benchmark, compliance with the 2018 legislation involves costs of about **US$74 billion per year** through 2030, or 1.4 percent of GDP annually. This reduces mean population exposure to $PM_{2.5}$ in South Asia to about 47 μg/m^3 in 2030, compared with 50.5 μg/m^3 in 2018 (Figure 3.8).
- Full implementation of all technically feasible emission controls as outlined in the 'Maximum technically feasible emissions reduction scenario' would cut exposure in 2030 to 17 μg/m^3, a reduction of two-thirds of 2018 levels, at a cost of **US$86 billion per year,** or 1.6 percent of GDP, on top of the cost of implementing the 2018 legislation. Expressed differently, the annual cost of reduced exposure per microgram per cubic meter is US$2.6 billion.
- Upscaling the current emission controls as outlined in the '*Ad-hoc* selection of measures scenario' would reduce mean exposure to 37 μg/m^3, a reduction of about one-quarter of 2018 levels, at additional costs beyond those of the 2018 legislation of **US$10.6 billion per year,** or 0.20 percent of GDP annually through 2030.
- Focusing on the most-polluted areas by bringing down exposure everywhere below the WHO Interim Target 1 of 35 μg/m^3 as outlined in the 'Compliance with WHO Interim Target 1 scenario' halves the mean exposure in South Asia to 26 μg/m^3, due to the co-benefits of upwind measures at other locations. Additional costs increase to **US$19 billion per year,** or 0.35 percent of GDP annually through 2030. Interestingly, at a cost of US$780 million per microgram per cubic meter of reduced exposure, the cost-effectiveness of these two last approaches is broadly similar.

- The most cost-effective air quality improvements emerge from a common but differentiated move toward the WHO Interim Targets, as outlined in the 'Toward the next lower WHO Interim Target scenario'. If each region were to cut exposure below the next lower Interim Target, mean exposure in South Asia would decline to 30 μg/m^3, a reduction of 40 percent of 2018 levels. Additional annual costs amount to **US$5.7 billion per year**, or 0.11 percent of GDP annually through 2030. Notably, costs of such an approach are 45 percent lower than those of the '*Ad-hoc* selection of measures scenario', while it would deliver 70 percent higher reductions in total exposure in South Asia. At US$278 million per microgram per cubic meter of reduced exposure, this approach in the most cost-effective.

The 'Toward the next lower WHO Interim Target scenario' maximizes cost-effectiveness by identifying the measures that deliver differentiated exposure targets at the least cost for each region. While the analysis was carried out for each of the 31 study regions, Figure 3.9 presents the impacts of individual measures on mean exposure levels in six aggregated areas, namely the Indo-Gangetic Plain, other regions of India, Bangladesh, Nepal, Pakistan, and Sri Lanka. The blue bars indicate exposure improvements that will result from implementation of the 2018 legislation, the orange bars show exposure reductions from the cost-effective measures in the 'Toward the next lower WHO Interim Target scenario', and the gray bars outline the scope for further improvements from measures that are not cost-effective in this scenario. Depending on the sector, further improvements that fall into these gray bars include more expensive clean cookstove variants, control of smaller units in the power sector, and the retrofitting of vehicles to meet the equivalent of the Euro-6 emissions standard.[6]

This shift in AQM strategies is also reflected by the cost of control measures in various sectors that emerge. Out of the total cost of US$73 billion per year that is estimated for the implementation of the 2018 legislation across South Asia through 2030, the vast majority, US$55 billion, is for road transport, followed by US$12 billion for emission controls in the power sector (Figure 3.10). Implementation of all additional measures that are technically feasible would require a further US$86 billion per year; additional controls for mobile sources, such as agricultural equipment, would consume 45 percent of these costs.

In contrast, additional costs in the 'Toward the next lower WHO Interim Target scenario' amount to only US$5.7 billion per year, of which about half is due to measures in the household sector. About 40 percent of the cost of additional measures is linked to further controls on mobile sources, power generation and industry, which are already addressed in the 2018 legislation, while 10 percent emerges from the agriculture sector through, for

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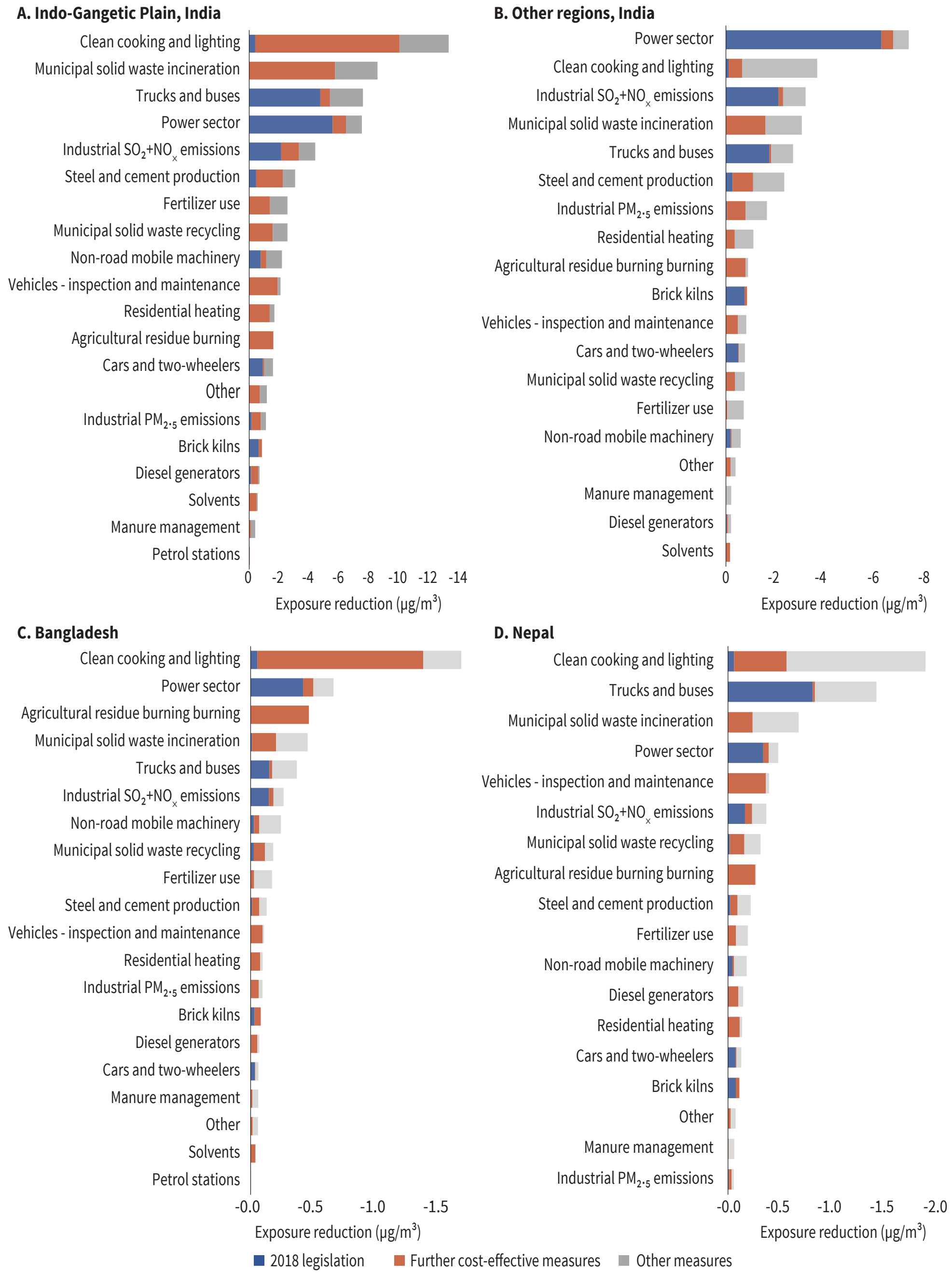
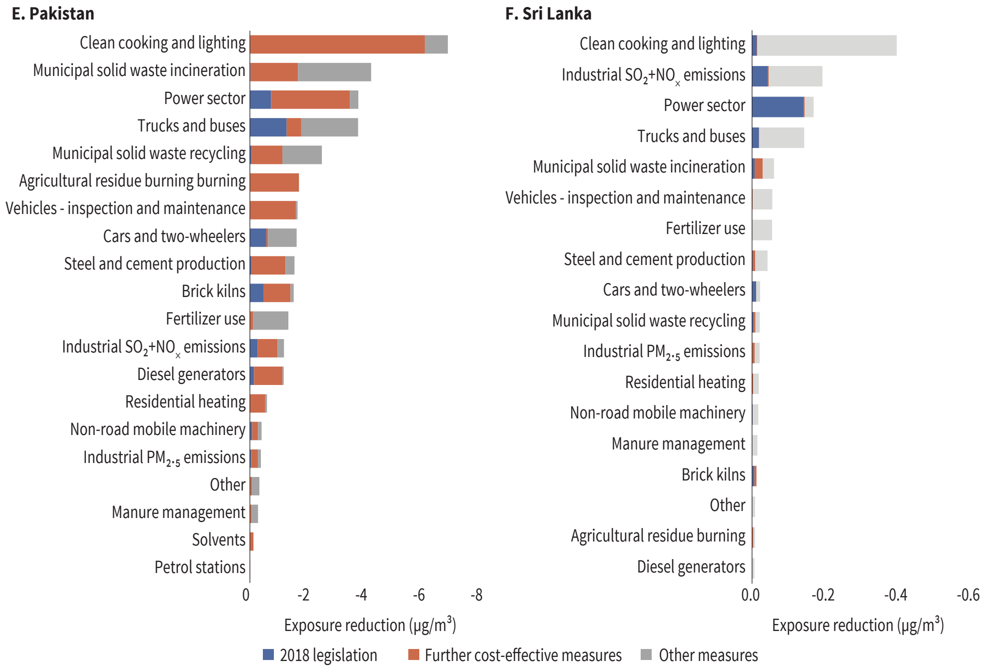
[6] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32012R0459

Figure 3.9. Impacts of emission control measures on mean exposure to fine particulate matter in South Asia in 2030



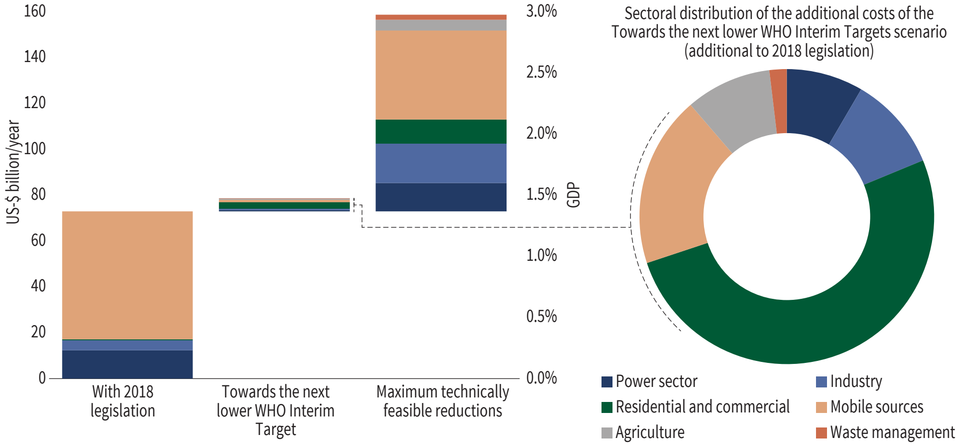
Source: GAINS calculations/IIASA (2021).
Note: The orange bars indicate the cost-effective reductions from the measures in the 'Toward the next lower WHO Interim Target scenario'. Scales on graphs vary. Fine particulate concentrations are in $\mu g/m^3$.

Figure 3.9. Impacts of emission control measures on mean exposure to fine particulate matter in South Asia in 2030 (continuation)



Source: GAINS calculations/IIASA (2021).
Note: The orange bars indicate the cost-effective reductions from the measures in the 'Toward the next lower WHO Interim Target scenario'. Scales on graphs vary. Fine particulate concentrations are in μg/m^3.

Figure 3.10. Additional costs beyond 2018 legislation by sector in 2030 under the 'Toward the next lower WHO Interim Target scenario'



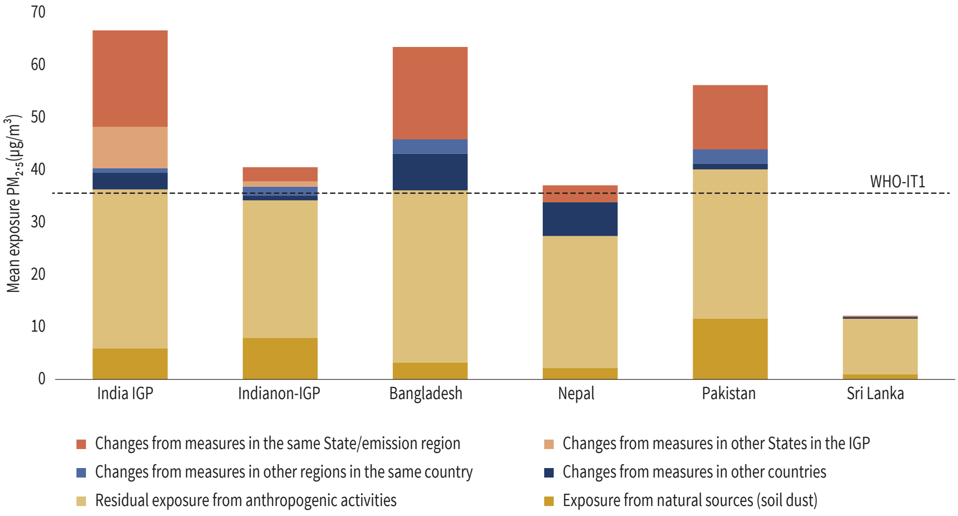
Source: GAINS calculations/IIASA (2021).
Note: Costs are in US$ billion per year and percent GDP.

example, measures to control agricultural waste burning, fertilizer application, and manure management.

3.2 Implications for AQM—the need for airshed-wide AQM

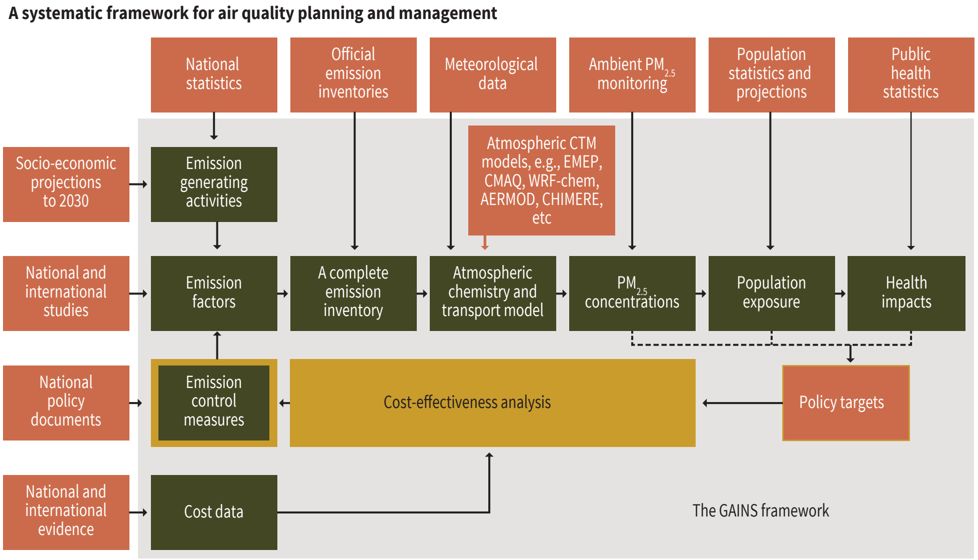
The important two-way transport of pollution across city limits, state boundaries, and even national borders becomes particularly relevant when considering cost-effective policy interventions to improve air quality without imposing excessive burdens on the economy. Especially in areas with high emissions density and topographic and meteorological conditions with air exchange with other regions, a lack of knowledge about action in other regions makes it impossible to determine effective sets of measures to meet a given air quality target, or to choose those measures that deliver the target at least cost. In the scenarios considered in this study, coordination across locations is the key feature that makes the 'Toward the next lower WHO Interim Target scenario' the most cost-effective. In the Indo-Gangetic Plain and Bangladesh, about 40 percent of the exposure reductions emerge from action taken in other states/countries, and this share is even higher in other areas that benefit from action in the most-polluted places (Figure 3.11).

Figure 3.11. Fine particulate matter exposure reductions in the 'Toward the next lower WHO Interim Target scenario' that emerge from measures within a region/country/state/province and from measures taken at upwind sources in others



Source: GAINS calculations/IIASA (2021).
Note: Fine particulate concentrations are in μg/m^3.

Figure 3.12. Data sources and calculation steps for the cost-effectiveness analysis using the GAINS model



Proven tools for a systematic cost-effectiveness analysis of AQM are available, but more reliable data are needed to provide robust quantitative policy advice. The strong mutual connections between pollution inflows from upwind sources and outflows into downwind areas open opportunities for AQM to enhance cost-effectiveness by balancing measures across regions in such a way that cost-savings and benefits from airshed-wide coordination are maximized. The GAINS model has proven effective in shaping cost-effective airshed policies in China and Europe (Figure 3.12).[7][8]

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[7] https://previous.iiasa.ac.at/web/home/research/researchPrograms/air/IR53-GAINS-CO2.pdf

[8] Lu, Zhenyu, Lin Huang, Jun Liu, Ying Zhou, Mindong Chen and Jianlin Hu. 2019. “Carbon dioxide mitigation co-benefit analysis of energy-related measures in the Air Pollution Prevention and Control Action Plan in the Jing-Jin-Ji region of China.” Resources, Conservation & Recycling: X.

CHAPTER 4

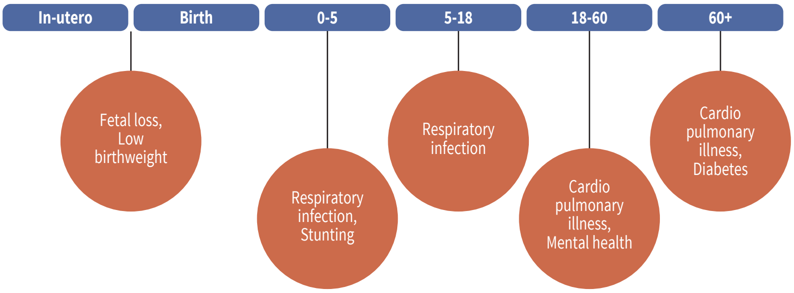
Benefits of Reduced Air Pollution

4.1 Health impacts of air pollution

The health impacts of air pollution range from respiratory infections to chronic diseases, and from serious discomfort to morbidity and premature mortality. Acute and sustained exposure to household and ambient air pollution can affect people at each phase in their lifecycle (Figure 4.1). Exposure to air pollution in-utero increases the probability of fetal loss, premature birth, and low birthweight. In early childhood, air pollution can cause respiratory infection and stunting (Heft-Neal et al. 2022). These early-life health impacts often persist into adulthood (Barker 1995; Currie et al. 2014; Almond and Currie 2011). For older children, adults, and the elderly, exposure to air pollution increases the risk of respiratory infection. Air pollution also poses a risk to mental health (Chen, Oliva, and Zhang 2018). A significant correlation has been found between exposure to air pollution for adults and the elderly, and the number of deaths caused by a multitude of non-communicable diseases (NCDs), including cardiopulmonary disease and type II diabetes, presumably because air pollution increases the likelihood of those diseases or it makes those diseases more likely to be fatal (K. Balakrishnan et al. 2019; Murray et al. 2020; Cohen et al. 2017). Although it is not easy to establish exact causes of diseases, several techniques have been employed over the years to estimate the impact of both household air pollution and ambient air pollution. This started with epidemiological studies using time-series and cohort studies. More recently, quasi-experimental methods, such as difference-in-differences and instrumental variable (IV) estimation, have produced estimates of the effect of air pollution on health (see Box 4.1).

Infants and children are especially vulnerable to air pollution, since lung development begins in-utero and continues in early childhood (Kajekar 2007). In-utero exposure to acute air pollution has been shown to increase fetal loss and infant mortality (Jayachandran 2009). Evidence is also found that in-utero and early-life exposure to sustained air pollution raises infant and child mortality (Greenstone and Hanna 2014; Goyal, Karra, and Canning

Figure 4.1. The potential health effects of air pollution across the lifecycle



Note: Other diseases are discussed in the Global Burden of Disease Study (K. Balakrishnan et al. 2019; Murray et al. 2020; Cohen et al. 2017).

2019). Every year, ambient air pollution is estimated to cause about 82,000 excess under-5 deaths in South Asia (Lelieveld, Haines, and Pozzer 2018).

In-utero exposure to acute and sustained air pollution also leads to a higher risk of low birthweight (Pedersen et al. 2013; Murray et al. 2020; Bharadwaj and Eberhard 2008). In turn, low birthweight is a risk factor for stunting (Goyal and Canning 2018; Sinharoy, Clasen, and Martorell 2020). Subsequently, the adverse effects, including lower educational attainment and earnings, can persist into adulthood (Barker 1995; Kajekar 2007; Currie and Vogl 2013; Currie and Almond 2011). Particulate matter can enter the brain during early stages of life and affect cognitive function (Brockmeyer and D'Angiulli 2016; Calderón-Garcidueñas et al. 2011; Suades-González et al. 2015). Respiratory infections can also affect children's physical growth, which subsequently can affect height later in life (Bobak, Richards, and Wadsworth 2004; Rosales-Rueda and Triyana 2019). And air pollution has been shown to affect educational achievement, proxied by test scores (U. Balakrishnan and Tsaneva 2021; Bharadwaj et al. 2017).

Air pollution can cause morbidity in adulthood through multiple channels. The correlation between chronic exposure to particulate matter and cardiovascular disease, respiratory illness, lung cancer, and type II diabetes is widely reported in the literature (K. Balakrishnan et al. 2019; Liu and Ao 2021; Al-Kindi et al. 2020). Recent evidence links air pollution to the probability of obesity (Deschenes et al. 2020) and COVID-19 infection (Yamada, Yamada, and Mani 2020; Mani and Yamada 2020; more details in Annex 4.2). Chronic exposure to air pollution is also linked to dementia (Bishop, Ketcham, and Kuminoff 2018; H. Chen et al. 2017), while acute air pollution is associated with poorer mental health (S. Chen, Oliva, and Zhang 2018).

Box 4.1. Empirical methods to estimate the effects of air pollution on health outcomes

The health effects of air pollution have been estimated for both household air pollution and ambient air pollution. An observed correlation between air pollution and health outcomes does not necessarily imply a causal effect of air pollution on morbidity or mortality. Other factors, such as socio-economic status, are possibly the true determinants of these health outcomes, while these factors are more prevalent in areas with severe air pollution. These factors that are correlated with both air pollution and health outcomes are called confounders. Different methods have been used to estimate the causal effect of acute and sustained air pollution on mortality and morbidity, while properly taking into account the confounders. In such studies, air pollution is measured by the average daily or annual concentration of Particulate Matter (PM), PM_{10} or $PM_{2.5}$ in micrograms per cubic meter (ug/m^3). PM_{10} ($PM_{2.5}$) describes inhalable particles with diameters that are 10 (2.5) micrometers and smaller (WHO 2021). $PM_{2.5}$ poses the greater risk to health and the latest WHO recommendation is exposure below 5 ug/m^3 annually and 15 ug/m^3 in 24 hours.

Time series studies. A typical time-series study correlates daily variations in morbidity or mortality in a city with monitored levels of air pollution. Such studies need to include time-varying confounders, such as weather, seasonality, or days of the week. It should be emphasized that such studies capture the effects of changes in acute, rather than long-term, exposure: the impact of a spike in pollution on a particular day on deaths or morbidity a few days later.

Time-series studies began in the 1970s and 1980s, with modern studies dating from the 1990s. Two notable multi-city time-series studies are the National Morbidity and Mortality Study (NMMAPS) in the United States (Samet et al. 2000), which covered more than 90 cities in the United States, and Air Pollution and Health: A European Approach (APHEA) conducted in 32 cities in Europe (Katsouyanni and APHEA Group 2006). Both found around 0.5 percent increase in total mortality per 10 ug/m^3 increase in PM_{10}.

Cohort studies. Prospective cohort studies follow a group of individuals over time and measure an association between longer-term exposures and morbidity and mortality. Pope et al. (2002) report significant impacts of exposure to $PM_{2.5}$ in cities in the United States on all-cause cardiopulmonary and lung cancer mortality. A 10 ug/m^3 increase in $PM_{2.5}$, comparable to a 50 percent increase in the level of Colombo's average $PM_{2.5}$

level,[9] is associated with an increase in non-trauma mortality by 4-6 percent. This work formed the basis of early studies of the global burden of air pollution (Cohen et al. 2004). The 2019 Global Burden of Disease includes meta-analyses of studies linking $PM_{2.5}$ to type II diabetes and low birthweight (Murray et al. 2020).

Quasi-experimental methods. Two common methods are difference-in-differences and IV estimation. Difference-in-differences compares the changes in outcomes over time between a population affected by air pollution, the treated group, and an unaffected (or less affected) population as the comparison group. Exogenous policy changes are evaluated to understand the causal effect of air pollution on health. When there is no exogenous policy change, the IV approach can be used. The instrument, an alternative variable, should be correlated with air pollution, but not affected by (unobserved) confounders. Moreover, the instrument should only affect health through its effect on air pollution. Therefore, the IV approach would capture the health effects of air pollution induced by the instrument. For example, thermal inversions exacerbate pollution events exogenously, hence they have been used as instruments to estimate the causal effect of exposure to air pollution. Globally, a 1 ug/m^3 increase in $PM_{2.5}$ induced by thermal inversions leads to a 0.5 percent increase in stunting rates (Heft-Neal et al. 2022).

There is a vast empirical literature using time-series and cohort studies, and all of them show the adverse effect of air pollution on mortality. To date, hundreds of time-series studies have been conducted throughout the world, including in Asia (Health Effects Institute 2011; Wong et al. 2008), showing similar increases in the impact of acute particulate matter exposure on mortality. Evidence from India finds a 0.8 percent increase in non-accidental mortality per 25 µg/m^3 increase in $PM_{2.5}$, with relative risk rising before tapering off above 125 µg/m^3, suggesting the non-linear effect of air pollution exposure (Krishna et al. 2021). United States cohort studies find that a 10 ug/m^3 increase in $PM_{2.5}$ is associated with an increase in non-trauma mortality of between 4 and 6 percent (Pope et al. 2002; Peters and Pope 2002). More recent studies from the Global Burden of Disease, beginning with Lim et al. (2012), use cohort studies and meta-analyses of epidemiological studies from many countries to quantify the impact of a wider range of $PM_{2.5}$ exposure on cardiovascular and respiratory deaths, as well as deaths from lung cancer and acute lower respiratory infection (Burnett et al. 2014).

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[9] Chapter 2 shows the $PM_{2.5}$ level in South Asia ranging from about 20 ug/m^3 in Colombo to almost 160 ug/m^3 in parts of Delhi National Capital Territory. The average $PM_{2.5}$ in the United States study is about 20 ug/m^3.

The premature deaths imply a reduced life expectancy by several years. The effect of ambient air pollution on the loss of life expectancy is estimated at 2.9 years globally, with a 2.5- to 3.3-year loss in South Asia (Lelieveld et al. 2020; Apte et al. 2018). Similarly, country-specific evidence from China and India, which generally experience higher levels of air pollution than high-income countries, suggests that air pollution is associated with a 1.7- to 5-year loss of life expectancy (K. Balakrishnan et al. 2019; Y. Chen et al. 2013; Ebenstein et al. 2017; Greenstone et al. 2015; Anderson et al. 2020; Ebenstein et al. 2015).

Much of the evidence on the health impacts of air pollution comes from high-income countries, although there is growing evidence from lower-income countries (Currie and Vogl 2013, Heger et al. 2019). Analyzing the health impacts specific to lower-income countries is important for several reasons. First, the level of pollution is generally higher in lower-income countries, and the effects of air pollution on health may be non-linear (Li et al. 2011; Zhao et al. 2019). Second, the sources of air pollution are different, and this may have implications for the health impacts. For example, natural and industrial sources are dominant in upper South Asia, while lower South Asia is more exposed to vehicular, industrial, and biomass burning (Singh et al. 2017). Across South Asia, cooking with solid fuels disproportionately exposes women and children to chronically high levels of air pollution (Krishna et al. 2017). Third, the underlying health distribution of the population may be different. For example, South Asians have greater risks of cardiovascular disease and diabetes, which manifest earlier than in white Europeans (Misra et al. 2017), and the 38 percent rate of stunting is higher in South Asia than the global average (Unicef). Fourth, the effect of air pollution on adult health is only observed conditional on survival to adulthood. Consequently, in settings with higher early-life mortality such as in many lower-income countries, the survivors may be highly positively selected, so the long-term effect of early-life negative health shocks such as air pollution may be less severe than in low early-life mortality settings (Bozzoli, Deaton, and Quintana-Domeque 2009). Fifth, the effect of air pollution on health may be highly dependent on behavior. Specifically, avoidance behavior may be more costly in lower-income countries due to limited access to health care and limited housing options, and these factors could increase the cost of air pollution in lower-income countries (Arceo, Hanna, and Oliva 2016; Moretti and Neidell 2011; Janke 2014; World Bank 2022).

4.2 Economic benefits of reduced air pollution

The positive health effects of lower air pollution outweigh the costs of pollution reduction. The improved wellbeing that comes with breathing cleaner air and the benefits of reduced morbidity and fewer premature deaths make it, in most cases, more than worthwhile to pay the economic costs of air pollution reduction, especially in a high pollution setting such as South Asia. However, there are also direct economic benefits of reduced air pollution (Frankenberg, McKee, and Thomas 2005; Kahn and Li 2019). Although an exact estimation of the economic benefits is not feasible, it is possible to perform rough cost-benefit analyses. Even with a conservative estimate of the benefits, these estimated benefits exceed the cost of air-pollution reduction in most scenarios that are analyzed in the previous chapter.

Reduced health expenditure, increased productivity, and more working days are the main economic gains of air-pollution abatement. The effects of air pollution on premature morbidity and mortality can be valued using a cost-of-illness (COI) approach. This measures the direct medical expenditure associated with disability or illness, including hospital, physician and medication costs, as well as long-term rehabilitation costs. When properly measured, out-of-pocket costs borne by affected individuals are included, as well as costs reimbursed by insurance or paid for by governments. The indirect costs of illness include time lost from work and the value of the caregivers' time (Landrigan et al. 2018). These costs also include losses in productivity over an individual's lifetime due to chronic medical conditions or a loss of cognitive function. Air pollution also negatively affects education and labor productivity through the days of missed school or work, and presence at school or work while unhealthy (Graff Zivin and Neidell 2012; He, Liu, and Salvo 2019; Chang et al. 2019; Aguilar-Gomez et al. 2022).

A lower-bound estimate of the benefit of reducing air pollution exceeds the cost for all of the countries studied in three of the four scenarios developed with the GAINS model in the previous chapter (Table 4.1)**.** The cost-benefit analysis is limited to the impact of reduced air pollution on stunting and does not take into account increases in life expectancy, given the difficulties in measuring the benefits of other economic effects of air pollution and in estimating the value of increased life expectancy (see the discussion of the cost-benefit analysis in Box 4.2). Thus, this analysis considerably underestimates the benefits of reducing air pollution. A benefit-to-cost ratio of greater than 1 implies that the benefits exceed the costs of the policy in a specific scenario (Table 4.1). In the most cost-effective scenario, the 'Toward the next lower WHO Interim Target scenario', with average $PM_{2.5}$ level of 30 μg/m^3, the gains in each individual country greatly exceed the costs. The same is true for two other scenarios. In the fourth scenario, however, the costs of achieving the Maximum technically feasible emissions reductions scenario are found to exceed the benefits, as the cost per capita would exceed the expected benefits from productivity gains for some countries. If that result still holds if all of the economic benefits of increased air pollution were accounted for, it could be a reason for cross-border trading. However, it is likely that the cost-benefit calculation will turn positive for most countries in the region with full accounting.

Box 4.2. Cost-benefit analysis of policies to reduce air pollution

The estimates of the additional annual cost for the South Asia region of four scenarios of reduction in air pollution (these are given in the previous chapter and are shown in Table 4.1 in the main text, below) are used as the cost in the cost-benefit analysis. The cost per country is assumed to be proportional to the country's population.[10] For a lower bound estimation of benefits, based on existing empirical literature, it is possible to derive estimates of reduced health-care costs and increased number of working hours for a given reduction in $PM_{2.5}$. However, many of the channels through which productivity is affected are difficult to quantify. The benefit calculations are limited to the productivity impact of stunting among children caused by in-utero exposure to air pollution as the impact of air pollution on stunting and the impact of stunting on productivity are well established. This means that the analysis is an underestimate of the total productivity benefits.

Another reason that the analysis is an underestimate of benefits is that it excludes the economic gains from decreased infant mortality and, in general, increased life expectancy. Although there is a rich literature surrounding the value of statistical life (Narain and Sall 2016; Robinson, Hammitt, and O'Keeffe 2019), this exclusion is necessary because estimating the value of increased life expectancy depends on data that are not readily available (Viscusi and Aldy 2003) and could depend on factors such as health status and age (Alberini et al. 2004).[11] The willingness-to-pay (WTP) approach assigns a monetary value to increased life expectancy by measuring preferences of people to avoid premature death, for example by estimating the wage premium paid to workers in more risky jobs, or by premiums people are willing to pay for life insurance. These preferences can also be measured with survey techniques that monetize preferences for improved health (Cropper, Hammitt, and Robinson 2011). A recent study by the World Bank (World Bank 2021) estimates that people would be willing to pay an amount equal to 10 percent of GDP in India and Nepal and 9 percent of GDP in Pakistan to eliminate premature death and years lost to disability due to both household and ambient $PM_{2.5}$ exposure. However, these measurements do not describe direct economic costs of reduced life expectancy. Rather, they monetize individual preferences and are therefore also not included in

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[10] Assigning cost proportional to the population would assign the highest cost to India. If the costs were assigned based on alternative measures, India could bear a lower share of the total cost.

[11] The economic loss when a person dies prematurely from air pollution could be measured as the discounted present value of the output that would have been produced during the remainder of the normal life expectancy without premature death. However, with current information it is not possible to determine the remaining life expectancy of the people who die prematurely from air pollution.

our cost-benefit analysis. In general, cost-benefit calculations that include an estimate of the benefits of increased life expectancy would result in a higher valuation of benefits. Later in this chapter, an estimate of the number of prevented premature deaths will be presented for each of the scenarios.

The economic gains of reduced health-care costs and increased working hours are calculated as the benefits in the year 2030. This matches the cost measures presented in the previous chapter, enabling a cost-benefit analysis. As in the previous chapter, the affected population is based on the projected 2030 population, estimated by age group[12] and average population growth based on the past five years' trend from the World Development Indicators (WDI). The net present value of the benefits from improved air is calculated with a 4 percent discount rate and a doubling of per person income (GDP per capita) by 2030. GDP growth after 2030 is assumed to be 6.4 percent (IMF). The effect of air pollution on the economic benefits that are measured is assumed to be proportional to the reduction in air pollution. The estimated reduction in health expenditure in 2030 is based on each country's per capita health expenditure as a share of GDP from the WDI. The estimated effect of air pollution on health expenditure is based on evidence that lowering air pollution to a safe level would reduce health expenditures by 10 percent (Gupta 2008).[13] The gain in hours worked is estimated to be 1.3 hours when air pollution improved by 20 percent (Hanna and Oliva 2016). The affected population is the working population aged 15 and 60. The effect is standardized by the average hours worked and the country's GDP per capita.

The productivity gains are calculated as the discounted future value in the year 2030. First, the effect of a 1 μg/m^3 increase in-utero exposure to $PM_{2.5}$ is associated with a 0.5 percent increase in stunting in the first five years of life (Heft-Neal et al. 2022). In South Asia, the average increase of $PM_{2.5}$ exposure in-utero is 18 μg/m^3, which would correspond to an 8 percent increase in stunting. This effect size is then converted to the stunting reduction associated with the $PM_{2.5}$ reduction under each scenario. The productivity gain from the potential stunting reduction is then calculated based on a 6 percent (5–7 percent range) GDP penalty due to stunting (Galasso and Wagstaff 2019). The affected population is children who would be born in 2030 since the effect on stunting is based on in-utero exposure. The affected children are assumed to work between the ages of 18 and 59.

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[12] https://www.populationpyramid.net/sources

[13] The reduction in air pollution considered by the study varies, but the average reduction attained by the *ad-hoc* selection of measures scenario is almost 30 percent, so it is used as the benchmark.

Table 4.1. Benefit-to-cost ratio in 2030 based on changes in morbidity

	Ambient $PM_{2.5}$	Additional cost	Additional benefits	Benefit-to-cost ratio					
Scenario	(μg/m³)	(US$ billion)	(US$ billion)	Bangladesh	India	Nepal	Pakistan	Sri Lanka	All countries
Ad-hoc selection of measures	37	10.60	34.11	3.56	3.20	1.88	3.32	2.47	3.22
Compliance with WHO Interim Target 1	26	19.00	63.01	3.67	3.30	2.04	3.42	2.55	3.32
Toward the next lower WHO Interim Target	30	5.70	52.50	10.18	9.16	5.68	9.50	7.08	9.21
Maximum technically feasible emissions reductions	17	86.00	86.63	1.11	1.00	0.62	1.04	0.77	1.01

Source: Authors' calculations.
Note: Present value of benefits from earnings gain from stunting reduction for children born in 2030, health expenditure saved for the population in 2030, and earnings gain from the working population aged 15 to 60 in 2030.

4.3 Preventing premature mortality

Reducing household air pollution (HAP) will reduce premature deaths due to both household and ambient air pollution. For many households in South Asia, the burning of solid fuels for cooking and heating is a significant source of direct exposure to $PM_{2.5}$, as well as of ambient air pollution. While the focus of this study is on ambient air pollution, the health impact of an additional microgram of ambient $PM_{2.5}$ depends on the levels of household exposure. Due to the concavity of exposure-response functions (Annex Figure 4.A.1), when HAP exposure is high, the marginal health impacts of ambient air pollution will be lower, and vice versa. It is also true that reducing HAP will improve ambient air quality—in parts of the Indo-Gangetic Plain, 30 percent of ambient air pollution comes from households (Chowdhury et al. 2019). Therefore, mortality risks from total $PM_{2.5}$ exposure from household, as well as ambient sources are estimated.

Baseline levels of exposure to fine particulate matter in 2030

Ambient exposure to air pollution in most of South Asia is expected to substantially exceed the WHO Guideline by 2030. The population-weighted average exposures to ambient $PM_{2.5}$

Box 4.3. Improved cookstoves and cleaner fuels in India

Policies to reduce household air pollution include switching to cleaner cookstoves, and replacing wood and coal with cleaner fuels. Improved cookstoves are designed to burn less fuel per unit of heat produced and remove smoke using a chimney. Studies have shown that improved cookstoves can substantially reduce indoor concentrations of particulate matter (Rehfuess et al. 2014). However, with a few exceptions, programs to promote the adoption of improved cookstoves have yet to yield sustained reductions in emissions (Smith and Pillarisetti 2017). Evidence from India suggests that the limited effect on emissions is partly due to inconsistent improved cookstove use (Hanna, Duflo, and Greenstone 2016).

Replacing solid fuels with cleaner fuels, such as liquefied petroleum gas (LPG), is another option. In India, the Pradhan Mantri Ujjwala Yojna (PMUY), designed to expand the use of LPG as a cooking fuel, has been successful in providing more than 70 million LPG cookstoves to poor households in the first 35 months of the program, and in increasing the supply of LPG. For the program to be successful in the long run, households will have to discontinue the use of polluting fuels and continue to purchase LPG (Kar et al. 2019).

in the baseline for 2030 range from 11.5 to 100 μg/m^3 in the 31 sub-regions (Table 4.2, with more details in Annex A.4.1), compared with the WHO Guideline of 5 μg/m^3. Ambient $PM_{2.5}$ levels will be highest in the Indo-Gangetic Plain and Bangladesh, where population-weighted annual average exposures will exceed 60 μg/m^3. Annual average exposures will exceed 100 μg/m^3 in many cities, including Delhi, Lucknow and Kolkata in India, while in Pakistan, Karachi is projected to experience ambient $PM_{2.5}$ of 75 μg/m^3. In western India—Rajasthan, Gujarat and Maharashtra—and the Punjab and Sindh regions of Pakistan, the annual population-weighted average $PM_{2.5}$ is projected to be about 45 μg/m^3. Exposures will generally be lower in the northeast and south of India and in Nepal. Population-weighted annual average exposure to ambient $PM_{2.5}$ in Sri Lanka is predicted to be 11.5 μg/m^3, still substantially higher than the latest WHO Guideline.

The high levels of household exposure underscore the health benefits of reducing the percentage of households burning solid fuels. Additional exposure to $PM_{2.5}$ in 2030 comes from HAP from burning solid fuels (Table 4.2; Box 4.3): 71 percent of households in Nepal, 60 percent in Sri Lanka, and 45 percent in Bangladesh and Pakistan. In India, 40 percent of households in the Indo-Gangetic Plain are assumed to burn solid fuels in 2030. Figure 4.3 shows the number of people, by grid cell, projected to be exposed to HAP in 2030. The number of those exposed is greatest in the Indo-Gangetic Plain, Bangladesh and in the Punjab and Khyber regions of Pakistan.

In households experiencing indoor air pollution, average indoor exposure is likely to exceed ambient exposure considerably. The additional exposure to $PM_{2.5}$ due to indoor air pollution is more than twice the level of ambient exposure in all major South Asian regions except India outside the Indo-Gangetic Plain (Table A.4.1 shows average household exposure, conditional on being exposed, and the results are summarized in Table 4.2). Exposures were estimated by the 2019 Global Burden of Disease (Global Burden of Disease Collaborative Network 2020) and reflect the type of fuel used for cooking and the nature of the stove employed.

Premature mortality associated with fine particulate matter in 2030

Air pollution is projected to account for 2.1 million premature deaths in 2030 in the five South Asian countries studied (Table 4.3).[14] Premature mortality associated with $PM_{2.5}$ is estimated for chronic obstructive lung disease, ischemic heart disease, lower respiratory infections, lung cancer, strokes and type II diabetes.[15] The estimation is done by calculating exposure for: (i) people exposed only to ambient air pollution; and (ii) people exposed to both ambient and HAP for each grid cell in the study area. Exposure-response functions from the 2019 Global Burden of Disease (Global Burden of Disease Collaborative Network 2020) are used to calculate, by disease, the fraction of deaths attributable to $PM_{2.5}$.[16] Deaths attributed to $PM_{2.5}$ account for a significant fraction of total deaths in each country: 20 percent in Bangladesh, 15 percent in India, 18 percent in Nepal, 17 percent in Pakistan, and 11 percent in Sri Lanka. In Bangladesh, India, and Pakistan, ambient air pollution accounts for about two-thirds of $PM_{2.5}$ deaths, while HAP accounts for one-third. The reverse is true in Nepal and Sri Lanka, where ambient $PM_{2.5}$ levels are, on average, lower and exposure to HAP higher (Table 4.3). Figures 4.4 and 4.5 map deaths attributable to ambient and household air pollution, respectively.

The burden of disease varies across countries, with ischemic heart disease accounting for the largest number of deaths, about 39 percent of the 2.1 million deaths, associated with $PM_{2.5}$ in 2030. Chronic obstructive lung disease is expected to account for 23 percent, strokes for 19 percent and lower respiratory infections for 8 percent of deaths associated with $PM_{2.5}$

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[14] Table A.4.1 presents estimates of deaths due to ambient and household air pollution for each of the 31 regions in the study area.

[15] Deaths due to each of these causes in 2030 are projected using the population estimates in this study and death rate projections from the Institute for Health Metrics and Evaluation (IHME) (Annex).

[16] The attributable fraction is multiplied by the baseline number of deaths for each group, by disease, to estimate the total deaths attributable to air pollution (Annex A.4.1). For people exposed only to ambient air pollution, deaths attributed to $PM_{2.5}$ are labeled as deaths attributable to ambient $PM_{2.5}$. For those exposed to both ambient and household air pollution, deaths attributable to ambient $PM_{2.5}$ equal total deaths attributable to $PM_{2.5}$ multiplied by the fraction of total exposure due to ambient air pollution.

Table 4.2. Projected population-weighted exposure to ambient and household fine particulate matter in 2030

Region	Ambient $PM_{2.5}$ ($\mu g/m^3$)	Households exposed to HAP (%)	Additional $PM_{2.5}$ exposure due to HAP ($\mu g/m^3$)
Bangladesh	61.4	45.0	125.0
Indo-Gangetic Plain, India	67.0	39.7	105.0
Non-IGP, India	33.4	28.0	80.0
Nepal	35.7	70.6	141.0
Pakistan	47.3	45.0	109.0
Sri Lanka	11.5	59.5	51.8

Source: Authors' calculations.
Note: Fine particulate concentrations are in $\mu g/m^3$.

(Table A.4.2). Type II diabetes, with 9 percent of deaths, and lung cancer at 3 percent, account for smaller fractions of deaths due to lower incidences of these diseases compared with heart and lung disease.

Reducing air pollution to lower premature mortality

Steps to reduce ambient and household air pollution could significantly reduce premature deaths. The scenarios outlined in Chapter 3 involve policies to reduce precursor emissions of ambient $PM_{2.5}$ from stationary and mobile sources, such as power plants, factories, and motor vehicles, and also reduce the number of households burning solid fuels. Deaths avoided in 2030 due to reductions in $PM_{2.5}$ according to the four scenarios range from 276,000 to 1,270,000, and the average cost per life saved for each scenario varies from US$7,600 to US$68,000 (Table A.4.3 describes ambient $PM_{2.5}$ levels and the percentage of households burning solid fuels after each policy has been implemented for each state and region, and Table 4.4 presents the average cost per life saved of each set of policies, calculated by dividing total air pollution control costs for the South Asia region by the aggregate number of deaths avoided). The impacts of these reductions in $PM_{2.5}$ on premature mortality are measured from baseline values of ambient and household air pollution in 2030, as described in the Annex. Due to the concavity of exposure response functions,[17] achieving greater reduc-

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[17] If exposure-response functions were not concave, the fraction of deaths attributable to air pollution would be astronomical. The concavity of exposure-response functions is caused by several factors. Data on active smokers show that there are limits to health effects from very high doses of particulate matter. Concavity also reflects the fact that sensitive people die at lower doses of particulate matter. Those who survive are more resilient.

Table 4.3. Projected premature deaths from exposure to fine particulate matter, 2030 baseline

Region	Baseline deaths	Deaths due to ambient $PM_{2.5}$ (%)	Deaths due to household $PM_{2.5}$ (%)
Bangladesh	186,000	63	37
Indo-Gangetic Plain, India	767,000	69	31
Non-IGP, India	876,000	67	33
Nepal	37,000	32	68
Pakistan	231,000	60	40
Sri Lanka	19,000	32	68
Total premature deaths	**2,116,000**	**66**	**34**

Source: Authors' calculations.

tions in $PM_{2.5}$ in states with already low levels of $PM_{2.5}$ yields higher marginal benefits than achieving similar reductions in states with higher baseline $PM_{2.5}$ exposures. Deaths avoided by each set of policies, by state and region, are presented in Table A.4.3 and summarized in Table 4.4 and Figure 4.2.

The effectiveness of air pollution control policies in reducing premature deaths varies greatly across policies and within regions. Under the '*Ad hoc* scenario', which reflects traditional air pollution control measures, 276,000 premature deaths are avoided, but it only reduces baseline deaths caused by air pollution in Nepal, Pakistan, and Sri Lanka by 3–4 percent (Table 4.4, Figure 4.2). The policies are slightly more effective in India, reducing deaths by 15 percent in the Indo-Gangetic Plain and, on average, by 16 percent in the rest of India. In Bangladesh, deaths are reduced by 7 percent. These policies come at a cost per life saved of US$38,000. In contrast, the policies in the 'Maximum technically feasible emissions reduction scenario' are much more effective, reducing premature deaths by 1,270,000, or 55–85 percent across countries. However, the average cost per life saved by these policies is US$68,000.

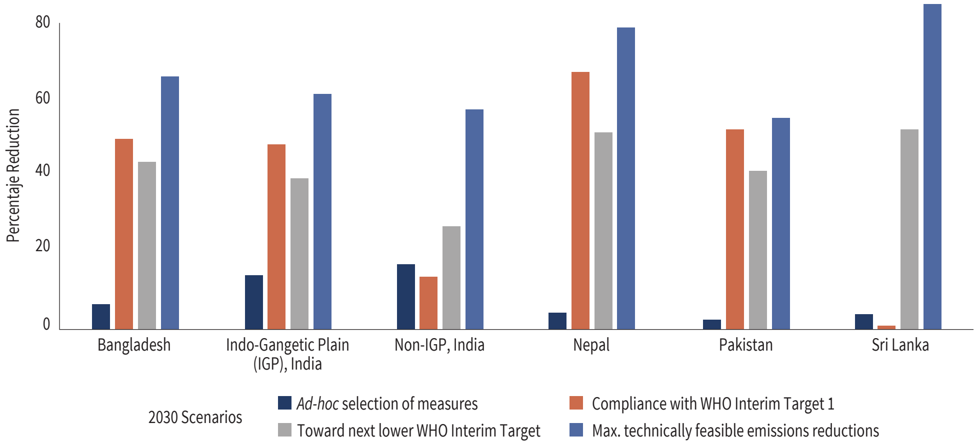
The analysis shows that the 'Toward the next lower WHO Interim Target scenario' with a $PM_{2.5}$ level of 30 $\mu g/m^3$ has the lowest per capita cost of averting premature deaths and the highest benefit-to-cost ratio for morbidities. Polices that make progress to the 'Toward the next lower WHO Interim Target scenario' save more lives—more than 750,000 annually—than policies in the 'Achieve WHO Interim Target 1 scenario', and at a much lower cost per life saved, at US$7,600, or only 11 percent of the cost under the 'Maximum

Table 4.4. Projected reductions in premature deaths from exposure to fine particulate matter by scenario, 2030

Region	Projected reductions in premature deaths by scenario in 2030 (%)			
	Ad-hoc selection of measures	Compliance with WHO Interim Target 1	Toward the next lower WHO Interim Target	Maximum technically feasible emissions reductions
Bangladesh	7	50	44	66
Indo-Gangetic Plain, India	15	49	40	62
Non-IGP, India	16	14	27	57
Nepal	3	67	52	79
Pakistan	4	53	41	55
Sri Lanka	4	1	52	85
Total number of deaths avoided	**276,000**	**739,000**	**752,000**	**1,270,000**
Cost per life saved (US$)	**38,000**	**26,000**	**7,600**	**68,000**

Source: Authors' calculations.

Figure 4.2. Projected regional reductions in baseline deaths due to exposure to fine particulate matter by region in 2030



Source: Authors' calculations.

technically feasible emissions reduction scenario'. Reductions in baseline deaths resulting from these lower cost policies show geographical variation. Specifically, the reductions in Sri Lanka and non-Indo-Gangetic Plain India are larger than the reductions from the set of

Figure 4.3. Projected number of people exposed to HAP, 2030 baseline

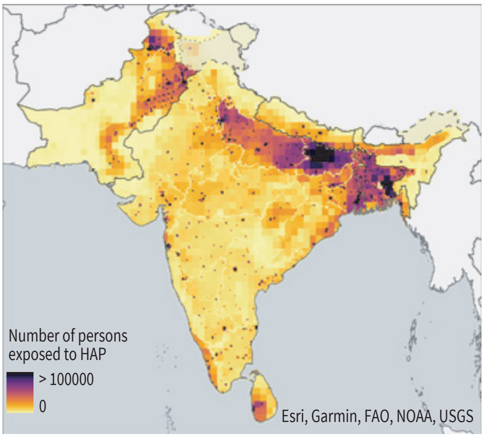
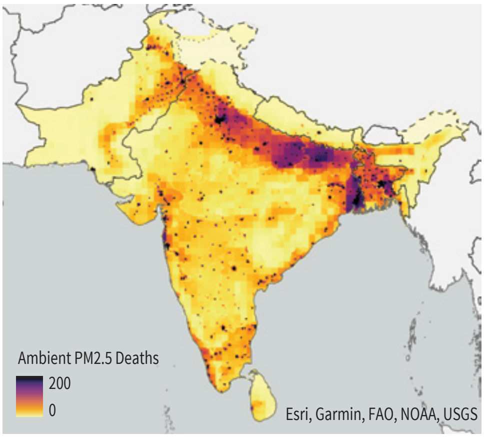
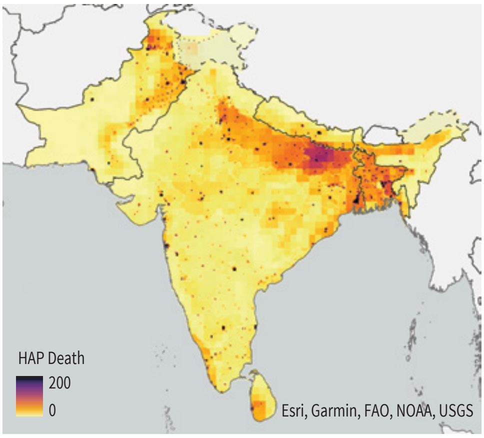


Figure 4.4. Projected deaths from ambient fine particulate matter exposure, 2030 baseline



policies in the compliance with WHO Interim Target 1 scenario', although the reduction in deaths is 10–15 percentage points lower in other regions of South Asia. The lower cost per life saved by the 'Toward the next lower WHO Interim Target scenario' policies is achieved by relying on reductions in the percentage of households burning solid fuels, which should also benefit more women and children.

Figure 4.5. Projected deaths due to household exposure to fine particulate matter, 2030 baseline



These benefits vary by location according to the geographical distribution of exposure to air pollution. The spatial pattern of ambient air pollution deaths (Figure 4.4) reflects population density and ambient concentrations. The modeling suggests that deaths will be highest in India's Indo-Gangetic Plain, Bangladesh, and in the Punjab area of Pakistan. The Indo-Gangetic Plain, which will contain 40 percent of India's population in 2030, will account for 47 percent of ambient air pollution deaths. The western states of Gujarat, Maharashtra, and Rajasthan, with 21 percent of India's 2030 population, will account for 22 percent, while states in the south of India—Andhra-Pradesh, Karnataka, Kerala, Tamil Nadu, and Telangana—which together will make up 22 percent of the country's 2030 population, will account for 18 percent of ambient air pollution deaths.

Deaths due to HAP mirror the geographical pattern of HAP exposure (Figure 4.3). Within India, 45 percent of deaths from HAP are predicted to occur in the Indo-Gangetic Plain, these states in central and eastern India—Madhya Pradesh, Odisha, and Chhattisgarh—contribute 17 percent of HAP deaths, while Gujarat, Maharashtra and Rajasthan contribute 16 percent, and Andhra-Pradesh, Karnataka, Kerala, Tamil Nadu, and Telangana, in the south of the country, contribute 13 percent. Although the absolute number of deaths attributable to HAP will be smaller in 2030 in Nepal, at 25,100 deaths, and Sri Lanka, at 12,600, than in India and Pakistan (Table 4.3), 68 percent of $PM_{2.5}$ deaths in Nepal and Sri Lanka will be attributable to HAP.

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Annex A.4.1. Health impact calculations

Formulas for baseline deaths

Let M represent total observed deaths (for some cause of death) in a grid square. Then

(1) $M = \lambda_T * RR(PM_A + PM_H) * pop * p_h + \lambda_T * RR(PM_A) * pop * \left(1 - p_h\right)$

where λ_T denotes the death rate at the background level of PM in each grid square, RR(z) is the relative risk of death at exposure level z, pop is the population of the grid square, and p_H is the fraction of population in the grid square exposed to both ambient air pollution (AAP) and HAP. Baseline deaths for each subgroup are given by

(2) $Baseline\ deaths_{AAP+HAP} = \lambda_T * RR(PM_A + PM_H) * pop * p_h$

(3) $Baseline\ deaths_{AAP} = \lambda_T * RR(PM_A) * pop * \left(1 - p_h\right)$

Equation (5) can be solved for λ_T

(4) $\lambda_T = \frac{M}{pop} * \frac{1}{RR(PM_A + PM_H) * p_h + RR(PM_A) * \left(1 - p_h\right)}$

and the result substituted into (6) and (7) to solve for baseline $deaths_{AAP+HAP}$ and baseline $deaths_{AAP}$.

Calculation of deaths attributable to ambient and household fine particulate matter

To compute the deaths attributable to ambient and household $PM_{2.5}$, deaths for each 0.1° x 0.1° grid square are calculated by cause of death, and then summed across all causes of death. First the calculations of ambient $PM_{2.5}$ (AAP) deaths (applied to each cause of death) are calculated allowing for exposure to HAP, followed by deaths attributable to HAP.

Ambient $PM_{2.5}$ (PM_A) affects both households that use solid fuels for cooking and those that do not. Let p_H represent the fraction of the population in a grid square that is exposed to solid fuels from cooking and PM_H represent their additional $PM_{2.5}$ exposure over and above PM_A. $1-p_H$ of the population is exposed only to PM_A. The total deaths due to $PM_{2.5}$ in the grid square (computed for each cause of death) is given by

(5) $PM\ Deaths = \mathrm{PAF}(\mathrm{PM}_A + \mathrm{PM}_H) * Baseline\ deaths_{\mathrm{AAP+HAP}} + PAF\left(\mathrm{PM}_A\right) * Baseline\ deaths_{\mathrm{AAP}}$

where baseline $\text{deaths}_{AAP+HAP}$ represents the total deaths among people exposed to both AAP and HAP and baseline deaths_{AAP} represents total deaths among those exposed only to AAP (see below for calculation of baseline deaths_{AAP} and baseline $\text{deaths}_{AAP+HAP}$). Let RR(z) represent the relative risk of death at PM = z. The population attributable fraction (PAF) is the proportion of deaths attributable to PM and is given by

$$(6)\ PAF(z) = \frac{RR(z) - 1}{RR(z)}$$

The PAF is evaluated at $z = PM_A + PM_H$ for persons exposed to both AAP and HAP[18] and evaluated at $z = PM_A$ for persons exposed to only to AAP. Baseline deaths for each sub-group in the population can be calculated from total deaths (M), p_H and the relative risk function, as described below.

The total deaths attributable to AAM are calculated as

$$(7)\ \textit{AAP Deaths} = \left[\frac{PM_A}{PM_A + PM_H} * PAF(PM_A + PM_H) * \textit{Baseline deaths}_{AAP+HAP}\right]$$

$$+\ PAF(PM_A) * \textit{Baseline deaths}_{AAP}$$

which assumes that AAP deaths among people exposed to both sources of particulate matter are proportional to the share of PM_A in total $PM_{2.5}$ exposure.

When deaths are calculated ignoring HAP, the term in the first line of (3) disappears, and baseline deaths_{AAP} are equal to total deaths (for each cause) in the grid square (M). Deaths attributable to HAP are given by

$$(8)\ \textit{HAP Deaths} = \frac{PM_H}{PM_A + PM_H} * PAF(PM_A + PM_H) * \textit{Baseline deaths}_{AAP+HAP}$$

Calculating deaths avoided by reducing PMA and pH

When air pollution control strategies reduce ambient $PM_{2.5}$, the improvement in PM_A constitutes a marginal reduction in $PM_{2.5}$. The deaths avoidable by reducing PM_A from PM_A^0 to PM_A^1 are measured by the reduction in the risk of death from moving from PM_A^0 to PM_A^1 multiplied by baseline deaths.

$$(9)\ \Delta M = \textit{Baseline death}_{AAP+HAP}\left(\frac{RR(PM_A^1 + PM_H)}{RR(PM_A^0 + PM_H)} - 1\right) + \quad \textit{Baseline death}_{AAP}\left(\frac{RR(PM_A^1)}{RR(PM_A^0)} - 1\right)$$

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[18] For a person for whom household air pollution is > 0, what is added to ambient $PM_{2.5}$ is a measure of total indoor exposure—which depends on type of fuel burned and amount of time spent indoors—minus ambient $PM_{2.5}$ exposure. Thus, "additional $PM_{2.5}$ exposure due to household air pollution" is added to ambient $PM_{2.5}$ to measure exposure for someone exposed to both ambient and household air pollution.

This formula assumes that neither PM_H nor p_H are affected by the policy. When either PM_H or p_H is altered, the change in deaths due to the policy is given by:

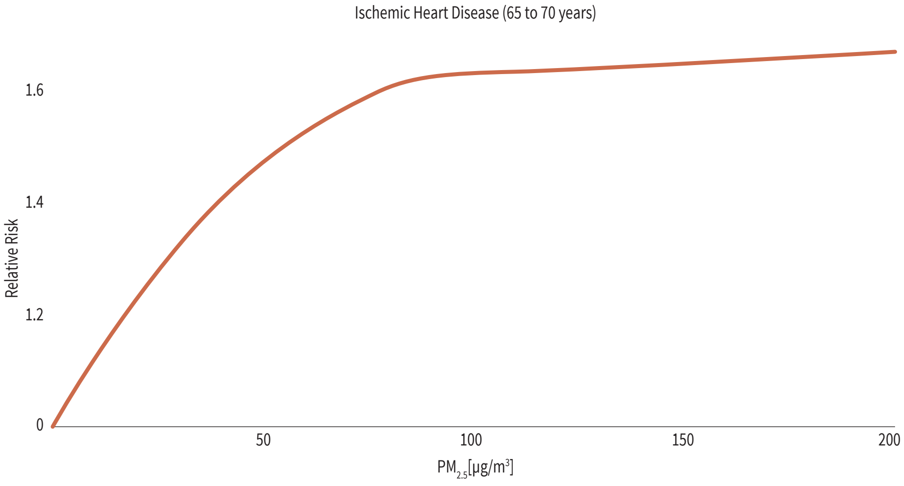
$$(10)\ \Delta M = Baseline\ death_{AAP+HAP}\left(\frac{RR(PM_A^1 + PM_H^1)}{RR(PM_A^0 + PM_H^0)} * \frac{p'_H}{p_H} - 1\right) + Baseline\ death_{AAP}\left(\frac{RR(PM_A^1)}{RR(PM_A^0)} * \frac{1 - p'_H}{1 - p_H} - 1\right)$$

Data Sources

The relative risk of death is computed as a function of total $PM_{2.5}$ exposure for each of the six causes of death: ischemic heart disease, stroke, chronic obstructive lung disease, lower respiratory infections, type II diabetes, and lung cancer. Exposure-response functions come from the 2019 Global Burden of Disease Study (Global Burden of Disease Collaborative Network 2020). Figure A.4.1 illustrates the exposure-response function for IHD for people aged 65–70 years.

To compute baseline deaths by disease in 2030 (M) estimates of population for each grid square from the International Institute for Applied Systems Analysis (IIASA) were used and deaths rates by disease from the Institute for Health Metrics and Evaluation (Institute for Health Metrics and Evaluation 2021). The proportion of the population in each region exposed to solid fuels (p_H) is estimated by IIASA. $PM_{2.5}$ exposure associated with HAP, conditional on being exposed, is given by region in Table A.4.1.

Figure A.4.1. Integrated exposure-response relative risk of ischemic heart disease, age 65–70 by fine particulate matter concentration



Note: Fine particulate concentrations are in μg/m³.

Table A.4.1. Exposure to ambient and household fine particulate matter and baseline deaths in 2030

Region	Sub-region	Ambient $PM_{2.5}$ (μg/m^3)	Households exposed to household air pollution (%)	Additional $PM_{2.5}$ exposure from household air pollution (μg/m^3)	2030 Baseline deaths due to ambient air pollution	2030 Baseline deaths due to household air pollution
Bangladesh	Dhaka	84.6	3.1	125.1	16,183	408
	Rest of country	59.1	49.2	125.1	100,471	69,074
Indo-Gangetic Plain (IGP), India	Bihar	67.8	55.8	138	88,780	70,254
	Delhi	99.2	2.0	45.0	34,162	247
	Haryana	72.2	27.5	71.0	32,690	6,656
	Jharkhand	49.5	49.1	111.4	26,821	21,558
	Punjab	55.1	12.0	65.3	37,281	3,708
	Uttar Pradesh	69.1	42.6	111.0	207,478	99,391
	West Bengal	62.4	34.8	91.1	101,366	36,974
Non-IGP, India	Andhra Pradesh-Telangana	28.9	20.6	63.1	70,963	23,372
	Assam	22.1	45.6	93.8	15,848	20,827
	Chhattisgarh	33.2	45.6	101.0	17,503	16,612
	Goa	32.5	7.5	40.8	1,644	122
	Gujarat	43.8	24.4	75.7	64,673	19,124
	Himachal Pradesh	15.5	43.4	63.3	2,858	3,931
	Jammu and Kashmir	16.4	25.2	74.0	6,231	5,226

Region	Sub-region	Ambient $PM_{2.5}$ (µg/m^3)	Households exposed to household air pollution (%)	Additional $PM_{2.5}$ exposure from household air pollution (µg/m^3)	2030 Baseline deaths due to ambient air pollution	2030 Baseline deaths due to household air pollution
	Karnataka	24.7	21.6	78.8	45,275	21,386
	Kerala	24.8	22.8	56.2	26,739	10,619
	Madhya Pradesh	35.3	41.7	111.5	54,510	45,465
	Maharashtra-Dadra-Nagar Haveli-Daman-Diu	45.6	20.5	66.1	120,907	29,334
	North East (excluding Assam)	25.0	27.8	74.1	9,514	6,031
	Orissa	34.6	48.1	96.3	28,427	26,829
	Rajasthan	42.8	39.7	109.4	58,164	37,979
	Tamil Nadu	22.7	13.3	66.9	58,977	15,918
	Uttaranchal	28.0	29.0	69.1	7,322	4,079
Nepal	Nepal	35.7	70.6	140.6	11,686	25,215
Pakistan	Karachi	74.6	11.8	109.2	17,459	1,680
	Khyber Pakhtunkhwa and Balochistan	35.6	62.0	109.2	20,678	29,149
	Punjab	48.8	43.0	109.2	80,531	49,484
	Sindh	44.0	45.3	109.2	19,100	13,222
Sri Lanka	Sri Lanka	11.5	59.5	51.8	5,997	12,645

Table A.4.2. Percent of baseline deaths associated with fine particulate matter by disease and region

Region	Chronic lung disease	Type II diabetes	Ischemic heart disease	Lower respiratory infection	Lung cancer	Stroke
Bangladesh	21	8	28	5	6	31
Indo-Gangetic Plain (IGP), India	26	8	38	9	2	17
Non-IGP, India	24	9	40	8	2	17
Nepal	26	9	35	9	2	19
Pakistan	12	9	47	6	3	24
Sri Lanka	8	22	39	6	3	22
Average	**23**	**9**	**39**	**8**	**3**	**19**

Table A.4.3. Reduction in deaths due to control strategies

Region	*Ad-hoc* selection of measures						
	Sub-region	Ambient air pollution	Exposed to household air pollution	Baseline deaths in 2030	Ambient air pollution under scenario	Exposed to household air pollution under scenario	Avoidable deaths under scenario
		(μg/m³)	(%)		(μg/m³)	(%)	(%)
Bangladesh	Dhaka	84.6	3	16,591	68.4	3.1	9
	Rest of country	59.1	49	169,545	46.9	49.2	6
Indo-Gangetic Plain (IGP), India	Bihar	67.8	56	159,034	48.1	42.1	15
	Delhi	99.2	2	34,409	75.9	1.4	10
	Haryana	72.2	28	39,346	58.2	19.6	11
	Jharkhand	49.5	49	48,378	37.8	36.2	15
	Punjab	55.1	12	40,990	46	8.3	11
	Uttar Pradesh	69.1	43	306,869	51.1	29.5	15
	West Bengal	62.4	35	138,340	46.5	27.2	14
Non-IGP, India	Andhra Pradesh-Telangana	28.9	21	94,335	23.4	14	16
	Assam	22.1	46	36,675	16.3	31.2	23
	Chhattisgarh	33.2	46	34,115	27.2	31	17
	Goa	32.5	8	1,766	27.7	5.2	11
	Gujarat	43.8	24	83,797	38.2	16.5	11
	Himachal Pradesh	15.5	43	6,789	12.5	29.9	22
	Jammu and Kashmir	16.4	25	11,457	12.3	17	23

Compliance with WHO Interim Target 1			Toward the next lower WHO Interim Target			Maximum technically feasible emissions reductions		
Ambient air pollution under scenario	Exposed to household air pollution under scenario	Avoidable deaths under scenario	Ambient air pollution under scenario	Exposed to household air pollution under scenario	Avoidable deaths under scenario	Ambient air pollution under scenario	Exposed to household air pollution under scenario	Avoidable deaths under scenario
(μg/m³)	(%)	(%)	(μg/m³)	(%)	(%)	(μg/m³)	(%)	(%)
36.2	0	39	42	0	33	25.5	0	53
28	0	51	32.7	0	45	16.5	0	68
28	0.6	55	39.5	9.8	38	16.3	0.6	71
35.8	0	43	42	0	37	31.4	0	48
28.8	0	48	35.6	0	39	26.3	0	51
31.3	49.1	12	35.1	9.9	35	17.9	7.5	58
21.8	0.2	50	31.6	0	34	19.4	0.2	55
24.7	0.4	56	34.5	0.1	45	20.6	0.4	62
35	3.8	38	38.1	2.7	35	18.5	2.7	61
24.9	20.6	7	25.1	15.5	11	12.7	0.2	57
16	45.6	8	17.2	27.6	25	6.7	0.1	80
27.2	45.6	6	26.2	17.2	30	15.5	0.9	62
27.7	7.5	10	26.3	2.1	17	14	0.4	50
33.8	24.4	11	35.4	6.2	21	25.3	0.2	40
8.4	0.1	70	11.7	9.4	49	5.5	0.1	80
6.8	0.2	70	12.1	2.9	47	4.9	0.2	77

Table A.4.3. Reduction in deaths due to control strategies (continuation)

Region	*Ad-hoc* selection of measures						
	Sub-region	Ambient air pollution	Exposed to household air pollution	Baseline deaths in 2030	Ambient air pollution under scenario	Exposed to household air pollution under scenario	Avoidable deaths under scenario
		(μg/m^3)	(%)		(μg/m^3)	(%)	(%)
Non-IGP, India	Karnataka	24.7	22	66,661	19.5	14.8	19
	Kerala	24.8	23	37,358	17.3	15.4	24
	Madhya Pradesh	35.3	42	99,975	30.1	28.4	15
	Maharashtra-Dadra-Nagar Haveli-Daman-Diu	45.6	20	150,242	36	14	14
	North East (excluding Assam)	25	28	15,545	20.6	19.1	18
	Orissa	34.6	48	55,256	27.2	34	17
	Rajasthan	42.8	40	96,144	38.1	27.5	12
	Tamil Nadu	22.7	13	74,895	17.2	9.3	20
	Uttaranchal	28.0	29	11,401	21.5	19.5	20
Nepal	Nepal	35.7	71	36,901	28.3	70.6	3
Pakistan	Karachi	74.6	12	19,139	66.2	11.8	4
	Khyber Pakhtunkhwa and Balochistan	35.6	62	49,828	31.1	62.0	2
	Punjab	48.8	43	130,016	41.9	43.0	4
	Sindh	44.0	45	32,322	41.0	45.3	2
Sri Lanka	Sri Lanka	11.5	59	18,642	9.4	59.5	4

Compliance with WHO Interim Target 1			Toward the next lower WHO Interim Target			Maximum technically feasible emissions reductions		
Ambient air pollution under scenario	Exposed to household air pollution under scenario	Avoidable deaths under scenario	Ambient air pollution under scenario	Exposed to household air pollution under scenario	Avoidable deaths under scenario	Ambient air pollution under scenario	Exposed to household air pollution under scenario	Avoidable deaths under scenario
(µg/m³)	(%)	(%)	(µg/m³)	(%)	(%)	(µg/m³)	(%)	(%)
21.9	21.6	6	20.5	4.1	29	10.7	0.5	61
22	22.8	6	21	4.1	27	7	0	73
25.1	41.7	10	26.3	3.5	41	19.1	0.5	56
35.2	20.5	11	35.7	3.4	22	19.5	0.5	49
15.9	27.8	15	17.3	8.4	36	10.3	1	63
27.1	48.1	7	28.2	7.3	37	14.2	0.8	66
27.8	0.1	44	32.6	5.5	33	25.7	0.1	47
19.7	13.3	8	19.5	1.8	24	7.8	0.1	66
13.2	0.0	58	18.7	3.7	42	8.8	0.0	71
18.2	0.1	67	25.4	8.1	52	10.2	0.1	79
36.1	0.0	35	37.5	0.0	33	34.7	0.0	36
21.3	0.0	57	26.3	0.0	49	19.8	0.0	59
18.9	0.0	57	28.6	0.0	43	17.3	0.0	60
30.9	0.0	37	34.3	4.1	31	29.2	0.0	40
10.8	59.5	1	10.9	6.4	52	3.4	0.0	85

Annex A.4.2. COVID-19 and air pollution linkages

There is also now growing evidence of increased rates of COVID-19 infection in areas with high levels of air pollution. Air pollution causes cellular damage and inflammation throughout the body and has been linked to higher rates of diseases, including cancer, heart disease, strokes, diabetes, asthma, and other co-morbidities. All these conditions also potentially increase the risk of death in COVID-19 patients.

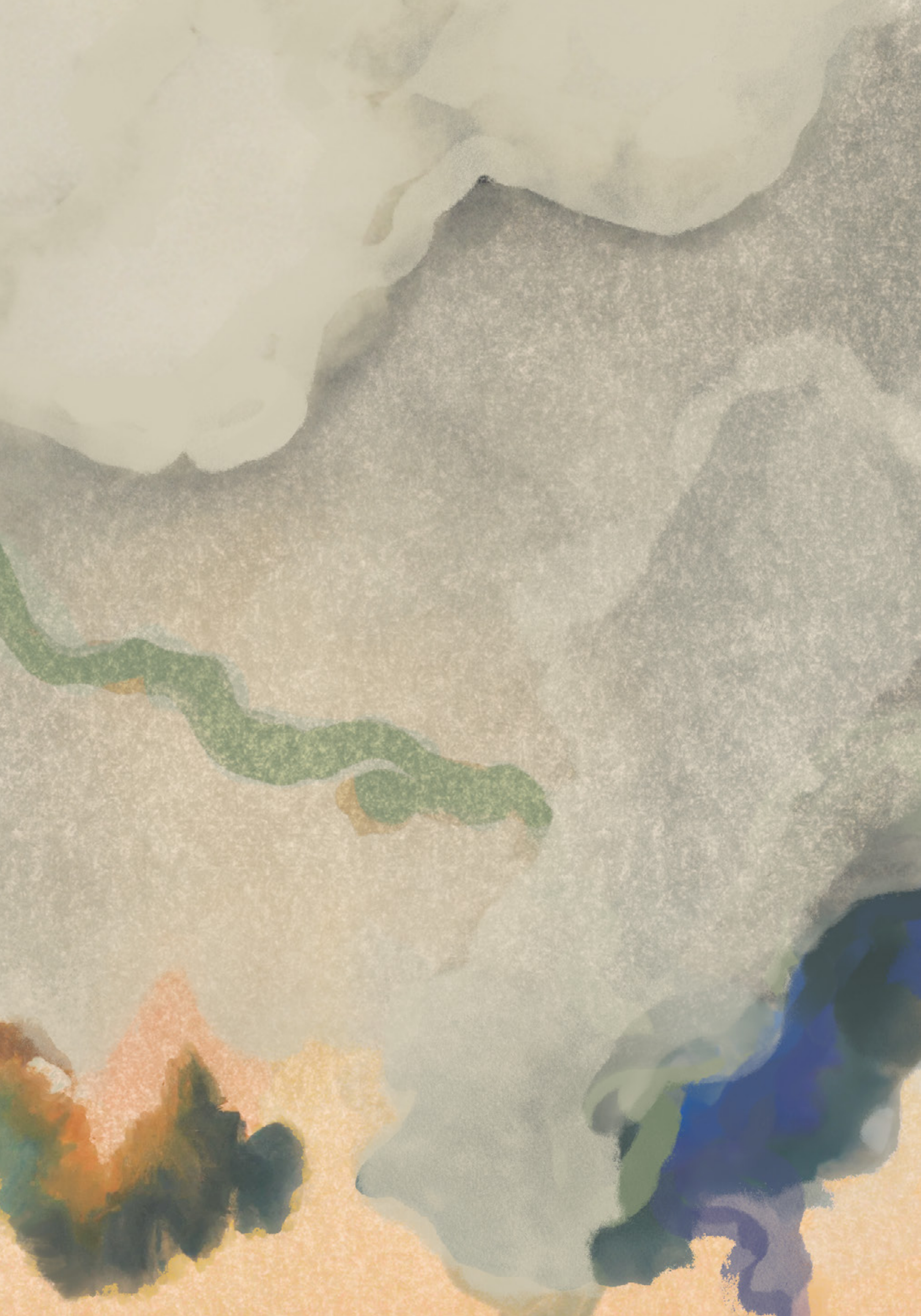
A study in the United States by Wu et al. (2020) found that someone living in an area of high-particulate pollution is 8 percent more likely to die from COVID-19 than others living in an area just one unit ($\mu g/m^3$) less pollution. This study and other similar studies conducted elsewhere and summarized below conclude that a small increase in long-term exposure to pollution can causes larger increases in the COVID-19 death rate. Given that the South Asia region is one of the major global hotspots for air pollution, one could therefore expect increased COVID-19-related cases and deaths linked to air pollution exposure.

In another study, Fattorini and Regoli (2020) attempt to provide evidence on the possible influence of air quality, particularly in terms of chronicity of exposure, on the spread COVID-19 in Italian regions. They show that long-term air-quality data are significantly correlated with cases of COVID-19 in up to 71 Italian provinces, providing evidence that chronic exposure to atmospheric contamination may be an important factor in the context for the spread of the COVID-19 virus. They conclude that atmospheric and environmental pollution should be considered as part of an integrated approach for human health protection and the prevention of epidemics from a long-term and chronic perspective.

Zhu et al. (2020) explore the relationship between ambient air pollutants and the infection caused by the COVID-19 virus in China, which experienced the first set of cases in the world. They use data from daily confirmed cases, air pollution concentration, and meteorological variables in 120 cities to investigate the associations of six air pollutants ($PM_{2.5}$, PM_{10}, SO_2, CO, NO_2 and O_3) with COVID-19 confirmed cases. Their findings suggest that a 10 $\mu g/m^3$ increase in $PM_{2.5}$, PM_{10}, NO_2, and O_3 was associated with a 2.24, 1.76, 6.94, and 4.76 percent increase in the daily counts of confirmed cases, respectively, at a 95 percent confidence interval.

Using spatial econometric technics, Cole et al. (2020) examine the correlation between long-term air pollution exposure and COVID-19 using data for 355 relatively small Dutch municipalities. They estimate long-term exposure to concentrations of $PM_{2.5}$, NO_2, and SO_2 on the number of COVID-19 infections, individuals hospitalized with COVID-19, and those who died because of COVID-19. Their results indicate that a 1 μ/m^3 increase in $PM_{2.5}$ concentrations is associated with 9.4 more COVID-19 cases, 3.0 more hospital admissions, and 2.3 more deaths.

Yamada et al. (2020) examine India's case, one of the most polluted countries in terms of ambient air pollution and HAP, and investigate links to the COVID-19 fatality rate using district-level data. The results suggested a positive and statistically significant association between the exposure to HAP and COVID-19 fatality rates. The estimation results indicate that a 1 percent increase in long-term exposure to $PM_{2.5}$ is associated with an increase in COVID-19 deaths by 5.7 percentage points, and an increase in the COVID-19 fatality rate by 0.027 of a percentage point, but this exposure is not necessarily correlated with COVID-19 cases. People with underlying health conditions such as respiratory illness caused by exposure to air pollution might have a higher risk of death following SARS-CoV-2 infection. This finding might also apply to other developing countries where high levels of air pollution are a critical issue for development and public health.



CHAPTER 5

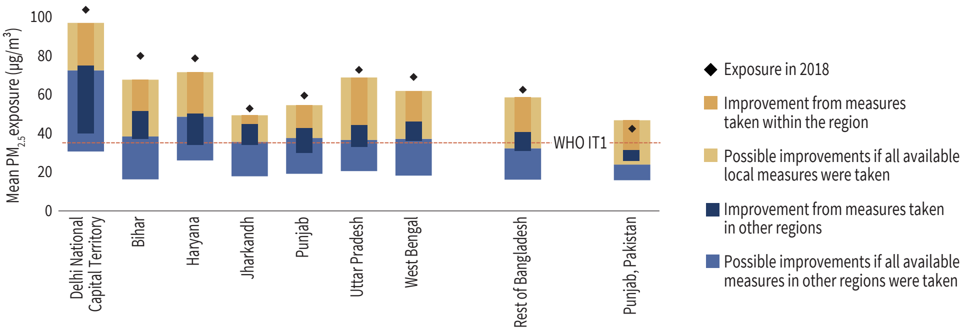
A Roadmap toward Airshed-wide Air Quality Management

Governments in South Asia are increasingly putting policies in place to reduce air pollution. The Draft Bangladesh Clean Air Act, India's National Clean Air Programme (NCAP), and the National Electrical Vehicles Policy in Pakistan are examples of these policies. The policies mainly focus on power generation, transportation, and large industries. Bangladesh, India, Nepal, Pakistan, and Sri Lanka have all imposed varying emission standards for vehicles, and mandate low-NO_x burners for power plants and filters for some large industrial boilers. With these policies, further worsening of air quality can be prevented even with substantial economic growth going forward. However, much more is needed to significantly reduce the current dangerous levels of air pollution.

In India, first steps are being taken to introduce cleaner cooking fuel for households, more efficient brick kilns, and better solid waste management. However, even after the full implementation of current policies, 30 percent of households in India will still be using biomass for cooking, while in the other two areas the transformation will be incomplete. That also means that in India significant progress at relatively low cost is still possible in these areas. In addition, abatement efforts (government investments and monitoring) in India, as well as other countries in South Asia, are still predominantly focused on large cities.

A major limitation of the current policies is that they focus on emissions and air quality within cities. Such an approach is insufficient because, in most South Asian cities, more than half of the air pollution originates from outside cities, while the polluting emissions inside cities worsen air quality far beyond city borders. In other words, air pollution in cities is part of the pollution in much larger airsheds caused by emissions from a wide range of sources. The problem of a city-focused approach is twofold. First, it is extremely expensive, if not impossible, to significantly improve air quality in cities with only in-city abatement policies, as these policies need to compensate for pollution that comes from outside the city, and abatement costs in industry and transportation are significantly higher than abatement in agriculture. Second, public support for such policies is limited because their impact on the

Figure 5.1. Fine particulate matter exposure reductions in the 'Toward the next lower WHO Interim Target scenario' from local measures in Indo-Gangetic Plain states/provinces and from measures taken in neighboring ones, compared with the full potential offered by all technically feasible emissions reductions in 2030



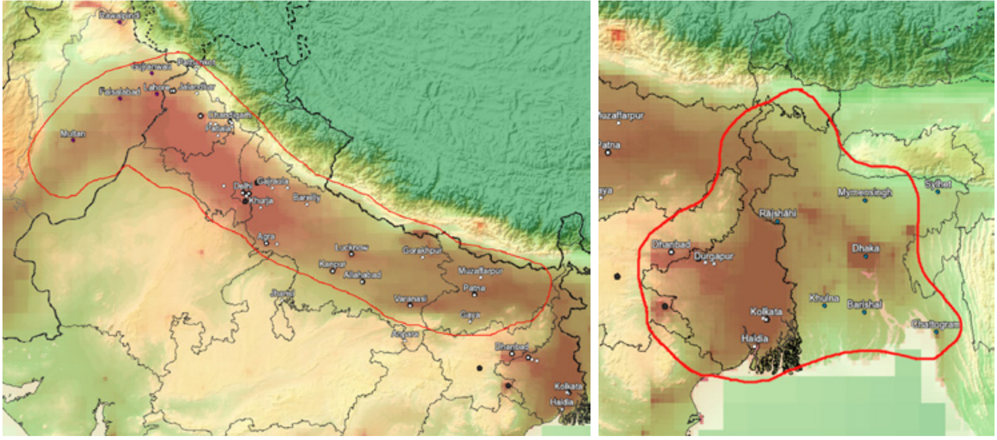
Note: Fine particulate concentrations are in µg/m^3.

city itself is limited. There is a great temptation for cities to blame neighboring areas rather than taking action themselves.

The limitations of a city-focused approach mean that cooperation between different jurisdictions within an airshed becomes crucial. If every one area can rely on the commitment by other areas in the same airshed, lower-cost abatement is sufficient to reach goals everywhere and support for abatement policies increases. This is illustrated in Figure 5.1 for the most cost-effective scenario discussed in Chapter 3. Even with maximum, and thus expensive, local efforts within the states/provinces of the Indo-Gangetic Plain, the local air-quality target (WHO Interim Target I) cannot be reached if areas outside the state/province do not also reduce emissions, while the target is easily within reach with combined efforts of all surrounding states/provinces. Such cooperation across different areas has the additional advantage of a level playing-field for producers in these areas: they all face the same restrictions on polluting forms of production. Once such a level of coordination is in place it becomes possible to achieve least-cost improvement in air quality by reducing emissions more in places where abatement costs are initially lower. Such solutions require economic incentives so that the burden of the abatement costs is shared by everybody who benefits from the emission reductions. This can be done by establishing regional funds or even by introducing a system of tradable emission rights.

Airsheds do not recognize national borders. Based on the analysis in Chapter 2, Figure 5.2 provides two examples of airsheds in the Indo-Gangetic Plain (IGP), including states/provinces, or other jurisdictions of India, Nepal, and Pakistan. The first airshed covers the western and central parts of the IGP, and the second covers the eastern part of the IGP. Given the

Figure 5.2. Suggested airsheds in the Indo-Gangetic Plain



Panel A. Suggested airshed covering the western and central parts of the IGP

Panel B. Suggested airshed covering the eastern part of the IGP

Source: Authors' calculations.
Note: Colors indicate $PM_{2.5}$ concentrations in 2018, measured in $\mu g/m^3$.

predominant wind direction from the northwest to the southeast, 30 percent of the air pollution in the Indian state of Punjab comes from Punjab Province in Pakistan and, on average, 30 percent of the air pollution in the largest cities of Bangladesh (Dhaka, Chittagong, and Khulna) originates in India. However, during some months of the year, substantial pollution flows in the opposite direction across borders.

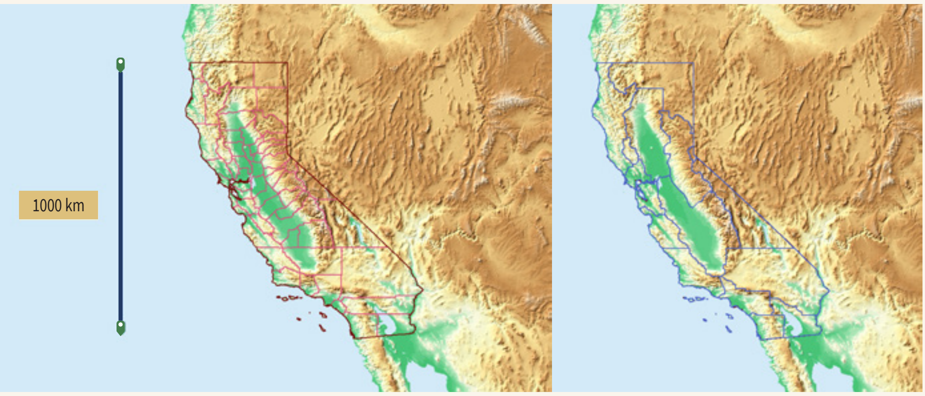
Establishing effective coordination is challenging, but several successful mechanisms to achieve this have been developed around the world. In the United States, Europe and China, air-quality policies have turned attitudes of blaming the neighbors and free-riding behaviors into constructive cooperation that delivered important public health and economic benefits. Common elements of these coordination efforts include: (i) an overarching regulatory framework that sets emission and air quality targets for participating jurisdictions; (ii) a well-funded central institution that ensures accountability and transparency; (iii) decentralized planning of abatement policies within the parameters set centrally; and (iv) economic incentives to reduce emissions, for example, through taxes and subsidies or by making access to funds conditional on abatement performance (see Box 5.1).

Building on the analysis in this report and on successful policy coordination around the world, a schematic roadmap toward airshed-wide AQM can be drawn. Such a roadmap consists of three phases, with each phase being broken down into three steps that can be distinguished (Table 5.1). The first phase sets the condition for airshed-wide coordination and cooperation. During this phase, the monitoring of air pollution is expanded beyond the big cities, data are shared with the public, credible scientific institutes that analyze the airshed

Box 5.1. Experiences around the globe with coordination to improve air quality

California: The state of California was one of the first places in the world to apply an airshed management approach. With a growing understanding that pollution from vehicles, power plants, and industry crossed county jurisdictions, California established 35 air-quality-management districts (AQMD) in the late 1950s that were then further grouped into 15 air basins (airsheds) closely following the topography of the state (Figure 5.3). To coordinate air quality management (AQM) throughout the state, the California Air Resources Board (CARB) was established with a mandate to manage air pollution sources that have state-wide impacts, mostly mobile sources, while each AQMD has the mandate to manage mostly stationary sources that can be controlled within its respective borders. The board also has the responsibility of building up the regulatory, technical, and administrative AQM capacity of the state. The state has committed a large group of staff and substantial financial resources to this activity. Each AQMD is responsible for planning, budgeting, and implementation within its respective AQMD. Further management planning and implementation coordination was established within each air basin. Finally, the implementation of this model has been incentivized by the federal government, as federal funds are withheld if the state fails to attain air quality standards. Based on the AQMD and air basin structure coordinated by CARB, the state has been able to improve from being the worst air quality location in the United States in the 1950s and 1960s to now imposing the strictest air quality standards in the country.

Figure 5.3. 58 counties organized into 35 AQMDs and 15 air basins in California, US



Note: Left panel shows 58 counties in California, right panel shows 15 airsheds.

Europe: After recognizing the importance of the long-range transport of air pollution and the resulting need for Europe-wide coordination for AQM policies, the 1979 Convention on Long-Range Transboundary Air Pollution (CLRTAP) emerged as the first multilateral agreement to address transboundary air pollution in Europe (Figure 5.4). It currently brings together 51 Parties, including the former socialist states in Eastern Europe, and the Russian Federation, as well as North America. Informed by a better understanding of air pollution science, the convention has since established systematic monitoring, reporting and verification mechanisms for ambient air quality, emission inventories, and policies and measures that are taken by the Parties to reduce their emissions. Eight protocols with specific obligations for the signatories to reduce emissions, among others, in the form of quantitative national emissions ceilings that limit the inflow of pollution from other countries, have led to a sharp decoupling of emissions from economic growth.

Acknowledging air pollution as an issue of political concern that requires a coordinated policy response to protect human health and the environment in a cost-effective manner, and to avoid undue distortion of economic competition among its 27 Member States, the European Union EU has established a more comprehensive framework of air pollution legislation. This legal framework assigns differentiated responsibilities to three administrative levels.

1. EU-wide legislation sets out the air quality objectives, the overall legal framework, and specific EU-wide requirements for ambient air quality, uniform source-specific emissions limit values and national emissions ceilings that all Member States need to meet.

2. Member States must transform all EU-wide legislation into national laws and report on progress, for example, on emission inventories, monitoring of ambient air quality, policies, and measures.

3. At the sub-national level, local authorities and city administrations are responsible for the licensing of individual plants, conducting air quality monitoring, and the development of AQM plans for their regions. If deemed promising, cities might also elaborate on local short-term action plans, although there are doubts about their effectiveness, especially for regional pollutants such as fine particulate matter.

China: Following a high pollution event in the North China Plain in early 2013, the Chinese Government established a collaboration between the Beijing and Tianjin

Figure 5.4. AQM in EU: Institutions, scale and responsibilities

Institutions	Scale (km)	Responsibilities
Europe-wide (EU)	~1,500	• Air quality limit values (uniform) • Uniform, source-specific emission limit values (BAT) • National emission ceilings
National governments	200-1,000	• Transposition into national laws
City administrations	20-50	• Licensing • Air quality monitoring • AQM plans • Local short-term action plans

municipalities, Hebei Province, and parts of the neighboring Henan, Shandong, and Shanxi Provinces—the so-called *expanded Jing-Jin-Ji area*—through which the Beijing Environmental Protection Bureau (EPB) was assigned to coordinate AQM planning and yearly revisions of the plans of the three jurisdictions (Figure 5.5). The area, which includes the Beijing and Tianjin municipalities and 26 prefectures, all pollution hotspots, has begun applying integrated airshed management. Since 2018, with the establishment of the Department for Regional Air Quality Management at the Ministry of Ecology and Environment, more power was given to the expanded Jing-Jin-Ji coordination body (established in 2013), which coordinates overall AQM planning and implementation. The Chinese Academy of Environmental Sciences (CRAES) supports the coordination body by determining cost-effectiveness and priority measures using a tailored edition of the GAINS program.

Figure 5.5. The "expandxed Jing-Jin-Ji" airshed with two municipalities and 26 prefectures in the North China Plain, China

Table 5.1. A roadmap toward airshed-wide AQM

Phases	Steps	Actions
Phase I Better monitoring and building institutions	1	Widespread installment of sensors and sharing of data
	2	Creation of credible scientific institutes that analyze airsheds
	3	Preparation of a whole-of-government approach
Phase II Additional and joint targets for cost-effective abatement	1	Installment of cleaner cookstoves
	2	Reduction of emissions from brick kilns and other small industrial firms
	3	Reductions of emissions from agriculture
Phase III Mainstreaming air quality management in the economy	1	Optimization of price incentives
	2	Mobilization of finance
	3	Creation of markets for emission trading

are created or strengthened, and national government moves to a whole-of-government approach. In the second phase, abatement interventions are broadened beyond the traditional targets of power plants, large factories and transportation. During this phase, major progress can be made in reducing air pollution from agriculture, solid waste management, cookstoves, brick kilns, and other small industries. At the same time, airshed-wide standards are introduced. In the third phase, AQM is mainstreamed into economic policy. During this phase, economic incentives are finetuned to allow private-sector solutions as much as possible to address distributional impacts and to exploit synergies with climate change policies. In this phase, trading of emission permits can also be introduced to optimize abatement across jurisdictions and across firms.

The phases in the roadmap may overlap when the rate of progress differs, depending on local circumstances. Introducing domestic policies will be easier and will go faster than establishing cross-border coordination. But now is the time to initiate cross-border coordination with the steps described in the first phase, even if some of the domestic initiatives have already moved on to a subsequent phase. If cross-border cooperation lags too far behind, then this will become an insurmountable obstacle to achieving effective and efficient solutions. The phases may also overlap in a different sense: the monitoring and analyses of pollution data will likely evolve throughout the process, as economic incentives trigger new technologies and sectoral shifts occur. On the other hand, the third phase already casts a shadow at the beginning of the process. Even if complete economic solutions are not yet available, it is important to keep the economic incentives in the line of sight from the start. For example, it is important to eliminate subsidies for polluting production methods as soon as possible. Nevertheless, despite these overlaps, the roadmap describes a logical sequencing. Better data are indispensable for any policy, so data collection and analysis should always come early on. Fully-fledged economic solutions across borders to allow for the compensation of countries as part of optimal abatement strategies is most challenging.

Phase I: More and better monitoring and improved institutions

Cost-effective AQM requires more comprehensive monitoring, enhanced scientific capacity, a shared knowledge base, and strong cooperation between governments. An expansion of reliable monitoring devices, also outside cities, is the first step in preparing for airshed-wide AQM. A common scientific knowledge base that quantifies key sources of pollution, atmospheric chemistry and transport processes, the costs of reducing emissions, and the benefits of clean air for human health and the economy will contribute to a shared understanding of the problems and solutions. Between governments, better cooperation is needed to align AQM with climate change policies, distributional policies, and other more general economic policies.

Step I.1: Widespread installment of sensors and the sharing of data

Emissions inventories are currently incomplete in South Asia. South Asia should move toward a comprehensive, unified inventory for the region that represents the full range of relevant emission sources, instead of relying on each city or state to develop its own individual methodology. International examples could be used as guidance, including from the U.S. Environmental Protection Agency, the European Monitoring and Evaluation Programme/European Environment Agency, and the Multi-resolution Emission Inventory (MEIC) in China. These will, however, need be tailored to local conditions in South Asia and extended to include the open burning of municipal waste, brick kilns, cremation, cookstoves, and many other practices.

Transparency and accessibility are important components of a monitoring system. The accessibility of data on unified platforms is critical to the sharing of knowledge and the building of trust across jurisdictions. Public awareness of air quality data can also help build support for AQM.

Monitoring systems need to be maintained and updated on an ongoing basis. Efforts will be required to ensure that any gains achieved will be sustainable. A monitoring, reporting, and verification system will be necessary not only to ensure compliance, but also to establish whether enacted policy reforms are having their intended effect. The information gathered through these processes can be used in future iterations of air quality programs to identify the most cost-effective solutions as South Asian economies grow and change. Several aspects of AQM are likely to evolve in the future. Technology will continuously improve, perhaps changing which policy choices are most cost-effective or even rendering some policy actions obsolete. The economic landscape is likely to shift as South Asian economies mature, including public attitudes toward risk and pollution.

Step I.2: Creation of credible scientific institutes that analyze airsheds

Scientific capacity in South Asia is currently well-developed in atmospheric science, but still relatively underdeveloped when it comes to capturing the region-specific sources of air pollution. Further development of the analytical capacity should also include research of the health impacts and analysis of the economic incentives and behavioral adjustments. In all these areas, there is a knowledge gap regarding the impact of specific circumstances in South Asia.

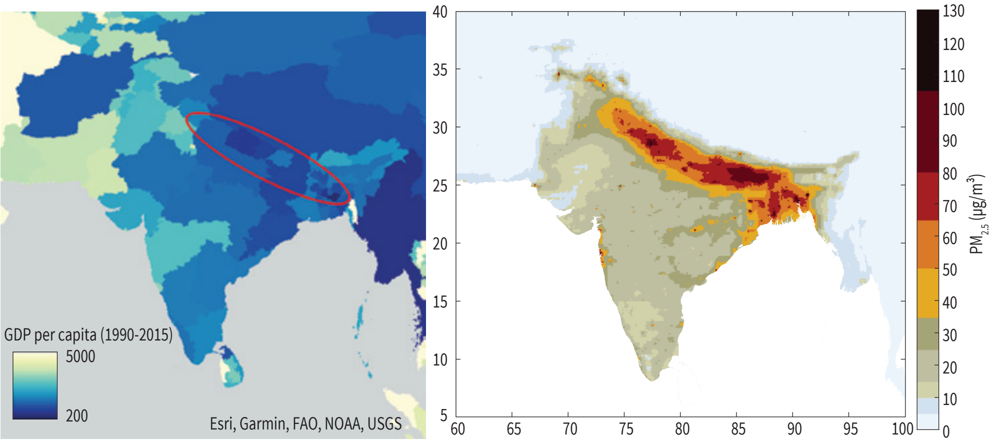
Scientific capacity should not be centralized, but rather distributed across the region. To enhance the credibility and salience of scientific information among the stakeholders of airsheds, and to ensure more equal representation and ownership across countries and jurisdictions, a region-wide scientific community on AQM should facilitate communication between experts across administrative boundaries and develop a scientific consensus on critical issues. There is already a move in this direction in India through the creation of the National Knowledge Network for Indo-Gangetic Plain States, comprising the Indian Institute of Technologies and other technical universities. However, it is not sufficient if these communities are confined within national borders.

Step I.3: Toward a whole-of-government approach

Ministries of the environment have the principal mandate to manage air-quality programs. However, many of these ministries in South Asia have neither the financial resources nor sufficient staff required for the needed coordination of environmental policies in agriculture, energy, industry, rural development, transportation, and urban development. As such, strengthening of the capacity of ministries of the environment at the federal and local (state, province, division) levels is needed for these ministries to advise other ministries and to coordinate across ministries.

A strong and central technical role of ministries of the environment should be complemented with a whole-of-government approach. AQM can have far-reaching consequences for other policy areas. Both trade-offs and synergies exist. While stricter emission standards can restrict energy supply in the short run, the development of renewable energy can increase future energy security. In addition, less reliance on fossil-fuel imports will help

Figure 5.6. High overlap between poverty and air quality in South Asia



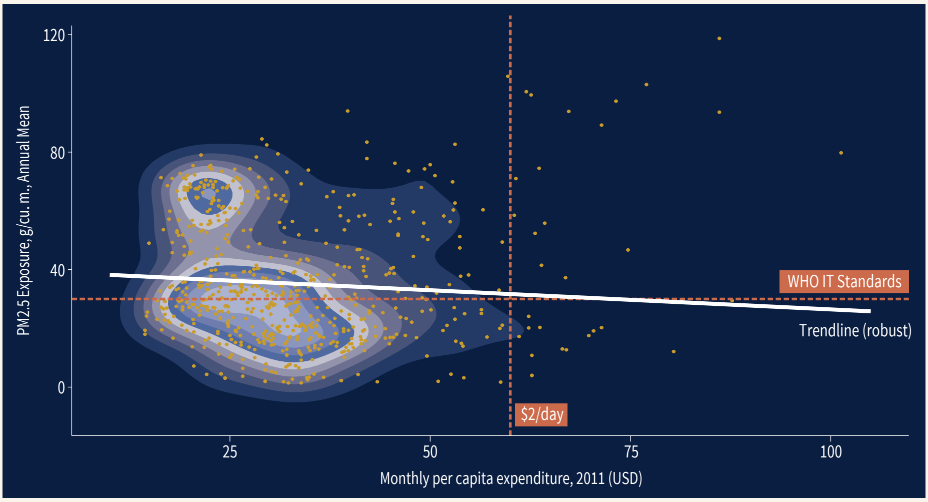
Source: Left panel: Kummu, Taka, Guillaume (2020); Right panel: GAINS calculations/IIASA (2021).
Note: Fine particulate concentrations are in μg/m^3. GDP per capita is in US$.

macroeconomic stabilization. There are strong synergies between AQM and reaching climate targets (see later in this chapter). Emission mandates in agriculture and industry affect the competitiveness of sectors. Therefore, common mandates across jurisdictions are crucial to maintain a level playing-field. Air pollution also affects requirements for health-care capacity (both in terms of size and in terms of focus on specific illnesses). For all these links between AQM and other policies, a whole-of-government approach is needed. Such an approach will help to ensure political support for AQM and reinforce consistency with the broader development strategy.

Distributional impacts of air pollution and abatement interventions are a prime example of the broader economic consequences of AQM. There is a significant overlap between local air quality and poverty in South Asia (Figure 5.6 and Box 5.2). Most developing countries have focused their efforts on the richest regions with a strong history of industrial and economic development. But in the South Asia region, air pollution is not only an urban or industrial problem. The average $PM_{2.5}$ concentration in the relatively poorer states of Uttar Pradesh at 97 μg/m^3 and Bihar at 87 μg/m^3 is among the highest in the world. At the same time, Uttar Pradesh and Bihar, located at the center of the most polluted IGP airshed, are also South Asia's largest "pockets of poverty" with over 115 million people with incomes below the US$2-a-day poverty line. The high overlap of pollution and poverty concentrations presents a unique opportunity, but also a challenge for South Asia. It means that a reduction in severe air pollution will benefit poorer households, improve their health, and enhance their productivity. But it also means that abatement costs will increase production and consumption costs in relatively poor areas. This could counteract policies that aim to alleviate poverty. This impact on poverty should be

Box 5.2. $PM_{2.5}$ exposure and per capita expenditure in India

Comparing $PM_{2.5}$ exposure against expenditure statistics for districts in India, there are two large clusters: (i) a main cluster is grouped just at or below WHO Interim Target 1 standard and includes a large group of districts with monthly expenditure of less than US$50 per capita; and (ii) a smaller cluster that includes a number of districts that are well above the WHO Interim Target 1 standard, while having even lower levels of per capita consumption. This smaller cluster represents the majority of districts over the WHO Interim Target 1 standard, showing that it is not just urban areas that experience high $PM_{2.5}$ exposure. Efforts to combat air pollution in South Asia must also contend with poverty in many of the most polluted districts in the region.

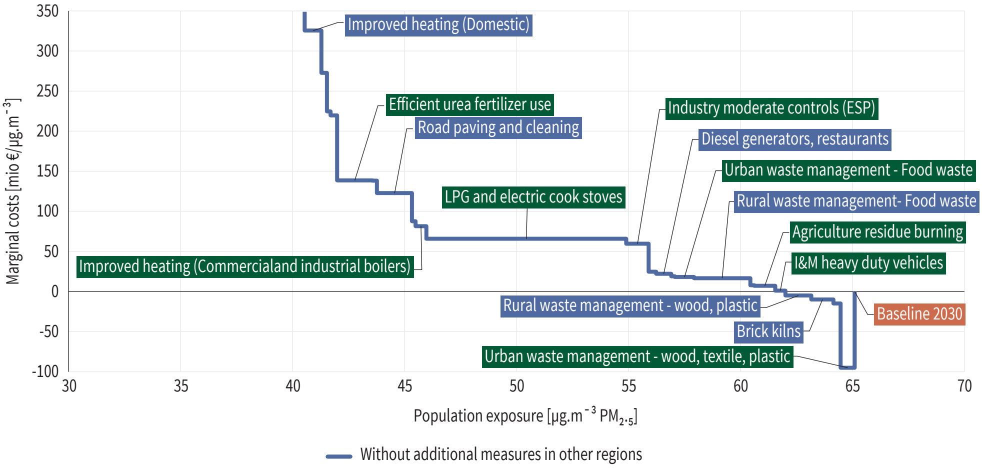


considered when decisions are made about the extent to which these abatement costs should be subsidized or whether households should be otherwise compensated for these abatement costs.

Phase II: Additional and joint targets for cost-effective abatement

Airshed-wide AQM will automatically include the abatement of more sources of air pollution. As mentioned earlier, current efforts in South Asia focus mainly on a small subset of emission sources in cities: transport, industry, and power plants. Once the focus broadens beyond cities, other emissions, which are important especially in South Asia, can be reduced. These include emissions from solid fuel use in households, from brick kilns and ovens in

Figure 5.7. Marginal costs for additional measures in Uttar Pradesh in 2030



Note: Marginal costs are in euro (million).

other small industries, from agriculture, and from open burning of solid municipal waste. Further research is also needed to clarify the contribution of ammonia from open sewage systems, particularly in the Central and Eastern parts of the Indo-Gangetic Plain.

Abatement costs in these additional sources of air pollution are relatively low. Figure 5.7 illustrates this with a marginal cost curve in the Indian state of Uttar Pradesh. This cost curve is based on the analysis underlying Chapter 3. It shows the marginal costs of abatement opportunities in addition to existing policies. A number of options are identified that could reduce air pollution at negative costs. For brick kilns and waste management, the upfront investments are compensated over their technical lifetime by cost savings from efficiency improvements or revenues from the sale of side products. Additional reductions can be achieved with measures with marginal costs of below €50 million per 1 $\mu g/m^3$ $PM_{2.5}$. These include, among others, stopping the open burning of agricultural residue and replacing traditional cremation practices with electric cremation. The largest single reduction potential is offered by universal access to clean cooking fuels (i.e., electricity and LPG) to eliminate solid fuel use in households.

In an airshed-wide approach, the reduction of air pollution should be achieved as much as possible with joint targets. Learning from experience within an airshed can lead to joint policies. Such an approach is optimal and maintains a level playing-field. While additional policies are also needed to further reduce air pollution from power plants, traffic, and large industries, the three steps during this phase focus on the additional sources of pollution in an airshed.

Step II.1: Switching to the use of cleaner cookstoves

Cleaner cookstoves are cost-effective, but implementation challenges remain. Reducing household air pollution by switching to cleaner cookstoves and using cleaner fuels for heating has been identified as one of the cost-effective measures for the region. Despite the effectiveness of clean cookstoves in improving health (see Box 4.3), three main challenges to long-term adoption remain: (i) initial and maintenance costs; (ii) knowledge and beliefs; and (iii) compatibility with end-users (Boudewijns et al. 2022). These challenges imply that economic support and information, in addition to adequate price signals, are key to achieving the adoption of clean fuel technology among mostly poor, rural households.

Step II.2: Reduction of emissions from agriculture and brick kilns

Agriculture in South Asia contributes to air pollution with the burning of fields and emissions of ammonia, mainly stemming from fertilizer use and manure management. The burning of fields results in high seasonal peaks in air pollution throughout the airsheds. Through chemical reactions in ambient air, ammonia is a substantial contributor of $PM_{2.5}$ in South Asia. The contributions from livestock to ammonia emissions could substantially grow over time. A study conducted in the United States suggests that livestock contributions to $PM_{2.5}$ can be up to 20 percent of total emissions, depending on the region and climatic conditions (Hristov 2011).

Policies that eliminate, or at least reduce, the burning of fields can be a cost-effective measure for the region. Recent evidence from India shows that cash transfers as payments for ecosystem services can reduce agricultural burning by up to 80 percent (Jack et al. 2022), while Indonesia's attempt to control agricultural burning through cash transfers has had mixed results (Falcon et al. 2022). Other examples of payments for sustainable agriculture have shown promising results in Latin America, and these may be adaptable to South Asia (Balseca et al. 2022).

Ultimately, the elimination of subsidies for the use of fertilizers and energy in agriculture should lead to more efficient fertilizer use in South Asia. However, in the short run, reforming these subsidies is challenging given the complex political economy involved. Other interventions can successfully lower fertilizer use without compromising productivity. For example, Bangladesh's simple rule-of-thumb training using colored leaf charts lowered fertilizer use by 8 percent without compromising yields, while China's outreach program and workshops for smallholder farmers lowered nitrogen use by one-sixth and increased yields by around 11 percent.

Large-scale intensive livestock operations can prevent emissions through the scrubbing of ventilated air both into and out of animal housing areas. Various types of air purification systems exist, including combination filters that remove more than one pollutant (Guo et al. 2022). Abatement measures for animals not contained within housing include a switch to low-nitrogen feed, the covered storage of manure, and application of manure on farms with technology designed to reduce ammonia emissions.

Less polluting and more viable brick kiln technologies are available but slow in being adopted. Many brick kilns in South Asia are very small units using old, inefficient technologies. The inefficient combustion of coal and agricultural waste by these kilns generate particulate matter and CO_2 emissions. Cleaner and potentially more cost-effective technologies already exist. For example, existing kilns can be converted to improved “zig-zag kilns” that produce lower emissions and are more efficient in brick production. It is estimated that the upfront cost of installing zig-zag kilns can be recovered in two to three years given their superior productivity (Bhattacharjya 2017). However, the adoption rate of zig-zag kilns remains low.

Tailoring successful technology adoption programs among small firms and farmers to the context of brick kilns could help. Because brick kilns are so small, numerous and spatially dispersed, a command-and-control approach to the diffusion of cleaner kilns is not feasible. Small firms in low- and middle-income countries are slow to adopt new technologies, even when those technologies appear to be cost effective. The possible reasons for low adoption include credit constraints, lack of information, and behavioral issues (Verhoogen 2020). Given the tiny size of kiln operations, the long payback period for zig-zag kilns and their relative novelty, any of these constraints could be holding back their diffusion. Information campaigns and financial incentives can work, but only if their design is tailored to the context and targets the right constraint (Cirera et al. 2019). Research to better understand why zig-zag kilns are not being more widely adopted would help identify the best program design.

Step II.3: Improved municipal waste management

Municipal waste is a significant source of air pollution in South Asia. In many cities in South Asia, no waste collection exists and, even in cities with high collection rates, the segregation of waste and recycling are rare. This leads to open dumping or incineration of mixed waste (Ferronato & Torretta 2019). Uncontrolled incineration of waste contributes to many types of air pollution, including $PM_{2.5}$, heavy metals, and volatile organic compounds (Wiedinmyer, Yokelson, & Gullett 2014). Open dumping releases methane, a powerful GHG.

Municipal waste management represents one of the most cost-effective potential interventions in the region. Modern disposal methods, including controlled incineration or chemical physical treatments, can provide significant air quality benefits at low cost. The most financially and environmentally friendly policies integrate multiple disposal processes: recycling, controlled incineration, composting for biodegradable waste, and managed landfills (Talang & Sirivithayapakorn 2021). By segregating waste in this way, each type can be optimally treated to reduce environmental impacts. For example, recycling programs are particularly important for plastics and electronic waste because of the toxic compounds released by the open incineration of these materials, and because precious or rare earth metals can be recovered from electronic components.

Phase III: Mainstreaming air quality in the economy

In the long run, the pricing of externalities through taxation or tradable emission permits should play a central role in AQM. In the short run, mandated emission standards, authorized filters or technologies, and bans of certain activities are the most effectives methods to reduce air pollution. However, these methods come with disadvantages. Emission standards reduce emissions per unit of economic activity, but they do not curb the total amount of polluting activity. Emission standards also do not incentivize the private sector to develop technologies that reduce pollution to levels below the mandated standards. If pollution has a cost, in the form of a tax or a price of an emission permit, total emissions are reduced more, and innovation is more stimulated. Taxation also has the advantage that AQM can be better integrated in other economic policies, meaning that synergies are better exploited, while tradeoffs are more easily optimized. Tradable emission permits facilitate the minimization of abatement costs across jurisdictions and across firms, as those with lower abatement costs are automatically compensated for more than proportional reduction in pollution. In this third phase, it will also be easier to mobilize private and public funds to reduce air pollution.

Step III.1: Taxation of air pollution

The taxation of activities that release pollutants will make cleaner technologies more competitive. Likewise, subsidies can encourage the use of clean industry and technology that do not harm air quality. In both cases, such tax and subsidy policies might stimulate the development of domestic and regional markets for the manufacture of cleaner technologies, and AQM infrastructure that drives down manufacturing costs and stimulates local operational and maintenance capacities.

Currently, most examples of taxes on air pollutants are found in developed economies. These taxes target primarily GHGs or cover only one type of source (typically, large power plants or large firms in high-polluting industries). However, developing countries are increasingly experimenting with direct taxes on pollutants. For example, China has an Environmental Protection Tax on $PM_{2.5}$ precursors (SO_2, NO_X, and soot), and Mexico imposed a carbon tax in 2014, which applies to CO_2 emissions from all sectors and covers all fossil fuels except natural gas. Meanwhile, in October 2021, Indonesia passed a law introducing a carbon tax on coal-fired power plants.

Subsidies on clean technologies exist in several large countries. For example, the U.S. Environmental Protection Agency's Targeted Airshed Program gives grants to projects that reduce ambient $PM_{2.5}$ pollution, including heavy-duty vehicle electrification, agricultural equipment replacement, alternatives to open burning, low-dust harvesting equipment and road dust. It is open to local and state pollution control authorities in targeted high-pollution areas across the country. Similar subsidy schemes exist in the EU and China. The Pradhan Mantri Ujjwala Yojana (PMUY) program in India, which supports the spread of liquefied petroleum gas (LPG), is another example of subsidizing cleaner technologies. Funding for such subsidies could come from reforming fossil fuel subsidies. Recent simulation shows that such reforms would improve air quality and health (Rentschler, Klaiber, and Dorband 2021).

Step III.2: Creation of markets for emission permit trading

Market-based approaches to controlling emissions, such as airshed-wide Emissions Trading Systems (ETS), can have significant advantages. An airshed industrial ETS would establish an airshed-level cap on total industrial emissions from participating firms and allow them to trade emissions permits. Such an ETS gives firms throughout the airshed more flexibility to adjust their emissions and incentives to innovate. In addition, it automatically provides pecuniary compensation across jurisdictions for abatement efforts. This could facilitate least-cost emissions reduction in the airshed. Examples of such environmental markets that target air pollution include the United States' RECLAIM program (introduced in 1994 to target SO_2 and NO_X), the Acid Rain program (1995 to target SO_2) and the NO_X Budget Trading Program (introduced in 2003). More recently, the Regional Greenhouse Gas Initiative (RGGI), a cooperative ETS among states in the Eastern United States seaboard, enables cross-state cooperation and trade in emission permits.

Recent evidence from a pilot ETS in India is encouraging. Until now, the experience and evidence base on ETS was wholly from select high-income countries. This is no longer the case: a pilot particulate matter ETS was recently introduced in the state of Gujarat among 317 high-polluting plants in the airshed of a large industrial city. A critical precondition for this scheme was the installation of a robust monitoring systems in the participating firms. The pilot has been evaluated through a randomized control trial, which shows that it reduced emissions significantly and at low cost relative to the existing command and control regulation (Greenstone et al. 2022). Other ETS programs are being piloted or are under consideration in Mexico, China, Thailand and Turkey. These are promising developments that help prepare South Asia for the third phase of AQM. However, it is too early to assess the scalability and sustainability of such pilot programs.

Step III.3: Mobilization of funding

An important advantage of the use of economic incentives is that they can mobilize funds from the private and public sectors for clean technologies. When the negative externalities of air pollution are incorporated into the price of technologies, it becomes profitable for the private sector to invest in clean technologies. The larger the area that imposes taxes, the easier it is for the private sector to invest at scale.

Economic instruments also generate government revenue that can be used to facilitate green innovation and address the distributional consequences of pollution abatement efforts. The funds from environmental taxes can play an important role in enticing cooperation within an airshed across jurisdictions. For example, the revenue generated from the RGGI scheme has been used to fund climate-related programs, such as energy efficiency measures in residential and commercial facilities and renewable power generation, and to address equity impacts by providing direct electricity bill assistance (RGGI, 2012). Several governments are linking revenues from carbon taxation to the funding of a “Just Transition” (World Bank 2022). For example, the EU ETS revenues will feed into the Social Climate Fund, which cushion the impacts of the ETS on vulnerable households, micro-enterprises, and transport users.

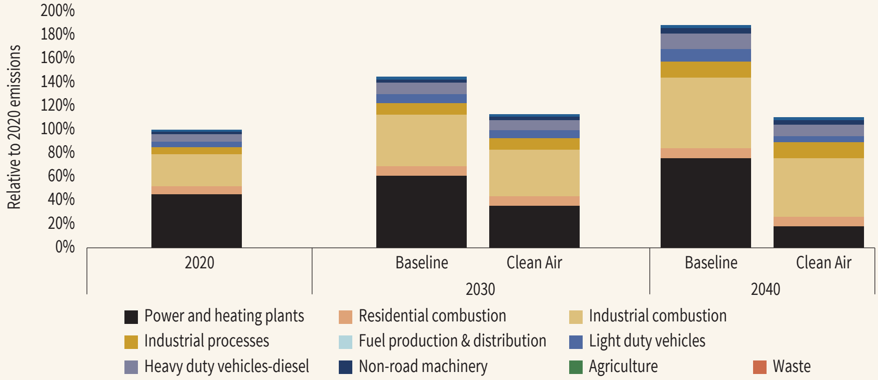
The synergies between reduction in air pollution and climate change policies can mobilize international funds. Strong synergies exist between meeting cleaner air target and meeting commitments to reduce GHG emissions (Box 5.3). Those synergies can help mobilize international funds that support pollution abatement or climate change mitigation. Some of these funds come from multilateral development banks, scaling up existing programs that link financing to the achievement of AQM targets. Though still falling short of what is needed to avoid the most dangerous impacts of climate change, total global climate finance has steadily increased over the past decade, reaching US$632 billion in 2021 (Climate Policy Initiative 2021). Debt (of which 12 percent was low-cost or concessional debt) is its largest component (61 percent), followed by equity investments (33 percent) and grant finance (6 percent). Only 5 percent of global climate finance flowed into South Asia in 2021. Developing a climate change strategy that emphasizes the synergies with air pollution abatement and enacting reforms that strengthen data and institutions for AQM could help South Asian countries gain better access to international funds.

Box 5.3. Synergies between AQM and climate change policies

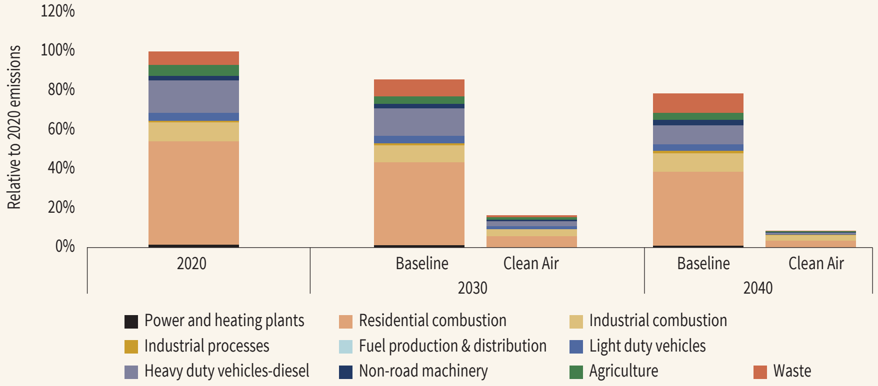
The climate impact is an important side effect of AQM. Although currently the reduction of GHGs may not rank highest on national policy agendas in South Asia, these reductions of CO_2, black carbon and CH_4 emissions would occur as a mere side-effect of cost-effective strategies aimed at bringing ambient $PM_{2.5}$ concentrations closer toward the WHO Interim Targets and gradually toward the WHO Guideline values. The implementation of clean air strategies helps to reduce CO_2, black carbon and CH_4. For example, reducing $PM_{2.5}$ concentrations to the WHO Interim Target 1 ($PM_{2.5}$ level of 35 μg/m^3) by 2030 and the WHO Interim Target 4 ($PM_{2.5}$ level of 10 μg/m^3) by 2040 could reduce CO_2 by 22 and 41 percent, black carbon by 81 and 89 percent and CH_4 by 21 and 28 percent, respectively (Figure 5.8).

Figure 5.8. Projected climate co-benefits in CO_2, black carbon, and CH_4 through implementation of clean air programs in South Asia to 2030 and 2040

A. Reductions in CO_2



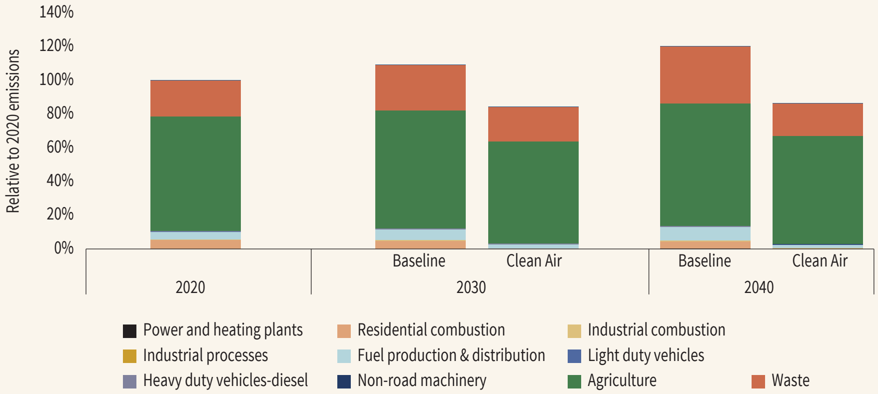
B. Reductions in black carbon



Source: Updates in estimations made by Markus Amann, IIASA et al. (2020) for this report.

Figure 5.8. Projected climate co-benefits in CO_2, black carbon, and CH_4 through implementation of clean air programs in South Asia to 2030 and 2040 (continuation)

C. Reductions in CH_4



Ample opportunities exist, but also serious obstacles remain

The roadmap above describes policy interventions that can achieve cleaner air in South Asia in a cost-effective way, but the road ahead is far from easy. The analysis in this report shows that, from a technical point of view, direct economic gains of better air quality exceed the abatement costs needed to reduce air pollution. However, it is not easy to achieve these optimal solutions. It requires the building of better monitoring systems, more scientific capacity, and better coordination between governments. It requires behavioral change among farmers, small firms, and households. It requires experiments with greening of tax systems and with tradable emission permits. International experience has to be finetuned to the specific conditions in South Asia. It requires cross-border coordination across the South Asia region. In particular, the latter is far from straightforward, but the time is now to put conditions in place for such cross-border cooperation and the time is now to travel the road to cleaner air. The rewards of advancing on the road are high, as the economic and social costs of lack of progress are hard to overestimate.

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