ACCELERATING ACCESS TO CLEAN AIR FOR A LIVABLE PLANET

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ESMAP
Energy Sector Management Assistance Program

GLOBAL PROGRAM ON SUSTAINABILITY
Making Nature Count for People & Planet

ABOUT THIS REPORT

Air pollution is taking a heavy toll on both people and economies across the world. Reducing it will require effective, targeted, and integrated policies.

This report identifies the main sources of air pollution in the world today, with a focus on ambient fine particulate matter ($PM_{2.5}$). It deploys scenario modeling to assess the extent to which current air pollution policies will reduce exposure to $PM_{2.5}$ by 2040, and to show how adopting an integrated suite of decarbonization and air quality management policies could yield significant progress towards clean air, with substantial co-benefits.

The report also assesses strategies and financing requirements to mobilize clean air investments, and emphasizes the features of effective air quality management governance.

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FOREWORD

Clean air is essential to our health, yet outdoor air pollution claims approximately 5.7 million lives every year. Most of the world's population breathes air that exceeds safe pollution levels, leading to a silent but deadly crisis. Air pollution is shortening lives, harming wellbeing, and affecting economic productivity. The burden is particularly severe in low- and middle- income countries where outdoor air pollution drives alarming rates of premature deaths and economic losses. As urbanization, economic activity, and population growth accelerate, more people are exposed to dirty air. This study highlights that air pollution accounts for a loss equivalent to nearly five percent of global GDP, a staggering loss that underscores the urgency of action.

Air pollution knows no borders and often travels across large transnational areas known as "airsheds". Its sources are diverse—ranging from transportation, industry, and agriculture. Addressing this challenge requires cross-sector and cross-jurisdictional collaboration, even among entities that traditionally compete for resources.

The good news is that improving air quality is both achievable and cost-effective within our lifetime. Because most air pollution originates from human activities, we have the power to control it. Countries and cities around the world have demonstrated that with the right policies and investments, air quality can improve—offering valuable lessons for others to follow.

Good examples of air pollution management already exist in countries and cities around the world. Mexico City implemented policies and measures to curb air pollution, reducing both pollution levels and the number of people exposed. In South Asia, regional partnerships in the Indo-Gangetic Plain and Himalayan Foothills region aim to cut pollution exposure across the airshed. In Africa, bioethanol cookstoves are being promoted in Rwanda and Kenya. Kyrgyz Republic is taking national-level actions to curb air pollution and create a revolving fund for clean heating. Meanwhile, financing mechanisms are supporting emission reduction projects in Egypt and Türkiye.

To make meaningful progress, we need a more ambitious and integrated approach toward air pollution—one that links conventional air quality management with broader policy goals, such as energy security or emission reduction. Strong governance, reliable air quality data, and commitment from policymakers will be essential in driving change.

A combination of public and private financing will be needed to accelerate access to clean air. Current financing for air pollution measures is insufficient, particularly in low and low-middle-income countries, where resources are already stretched thin. Expanding financing instruments, such as green bonds, concessional loans, guarantees, results-based financing, outcome bonds, and blended finance can unlock private-sector investments and position clean air as a viable economic opportunity.

Air pollution is one of the greatest health challenges of our time, but solutions are within reach. Every reduction in exposure will yield health and economic benefits. The knowledge, tools and resources exist—what is needed now are committed leaders ready to champion clean air for all.

Axel van Trotsenburg
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Acronyms, Abbreviations, and Units

AQM	Air quality management
CCM	Climate change mitigation
CO	Carbon monoxide
CO_2	Carbon dioxide
DFIs	Development finance institutions
EPA	United States Environmental Protection Agency
EU	European Union
GDP	Gross domestic product
GHG	Greenhouse gas
GWP100	Global warming potential over 100 years
IDA	International Development Association
IEA	International Energy Agency
IGP-HF	Indo-Gangetic Plain and Himalayan Foothills
LMIC	Low- and middle-income countries
LPG	Liquified petroleum gas
MSW	Municipal solid waste
$\mu g/m^3$	Micrograms per cubic meter
NDCs	Nationally Determined Contributions
NO_X	Nitrogen oxide
OC	Organic carbon
PM	Particulate matter
$PM_{2.5}$	Particulate matter less than 2.5 μm in diameter
PforR	Program for Results
PSL	Priority sector lending
RBF	Results-based financing
SO_2	Sulfur dioxide

MAIN MESSAGES

Ambient (outdoor) air pollution kills roughly 5.7 million people globally each year.[1] Its economic costs are estimated at nearly 5 percent of global GDP, accruing not only from poor health outcomes and the death burden, but also from productivity loss and cognitive impacts, which can span generations.

Ninety-nine percent of the global population is exposed to pollution exceeding guideline values, but the burden is highest in low- and middle-income countries, where low incomes and limited access to healthcare compound impacts and exacerbate existing inequalities across and within national boundaries. Taking a "business as usual" approach will only worsen these impacts.

The World Health Organization recommends avoiding average $PM_{2.5}$ concentrations above 5 micrograms per cubic meter (μg/m³), with interim targets of 35 μg/m³, 25 μg/m³, 15 μg/m³, and 10 μg/m³ on the way to achieving the 5 μg/m³ guideline. However, over the next 15 years, existing and currently planned policies are expected to lead to a 21 percent increase in the global population exposed to $PM_{2.5}$ concentrations above 25 μg/m³ (Interim Target 2). Already a crucial development challenge today, curbing air pollution will be imperative for future growth and prosperity on a livable planet.

Substantial progress is within reach. This report shows that halving the number of people exposed to $PM_{2.5}$ concentrations above 25 μg/m³ globally by 2040 is feasible and affordable. Because air pollution stems largely from anthropogenic sources, effective policies can reduce it. Heating, cooking, transportation, agriculture, and waste are key sectors requiring integrated policies. Quick-win priorities are apparent: solid fuel heating is a major issue in low- and middle-income countries, whereas residential cooking is a primary concern in much of Africa.

Across all contexts, successful policies and measures will hinge on efforts to:

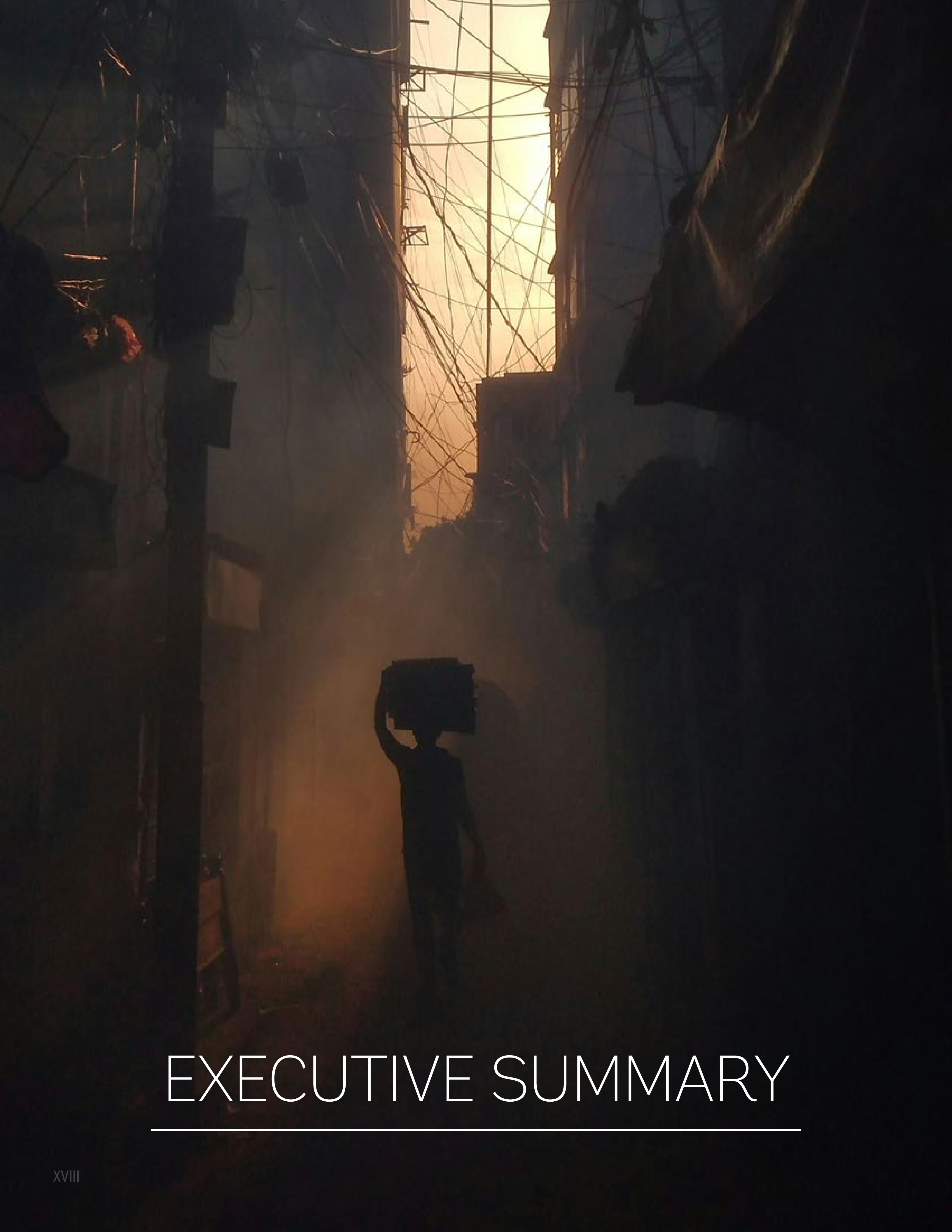
1. **Strengthen institutions**. Policy makers' most important action to accelerate access to clean air is to prioritize strengthening air quality governance. Countries with successful track records in curbing air pollution have placed clean air at the center of their economic and welfare agenda, making it an explicit public policy goal championed at the highest levels of government. The first step to strengthening institutions entails developing a strategic vision

that can be carried by core government agencies with the backing of high-level government champions. This vision will inform medium-term plans with enunciated goals, clear functions, and explicit lines of accountability across government agencies with adequate technical competencies and budget resources. Only then can empowered local governments (which are central for implementing airshed approaches) and effective multisector solutions (which are essential due to the wide range of air pollution sources) be deployed at scale.

2. **Leverage information**. Effective clean air policies and investments are grounded in sound evidence. Information—about air pollution sources, their impacts, and their drivers—is essential for unlocking action. However, most low- and middle-income countries still face substantial information gaps, starting with the extent and quality of their monitoring networks. A lack of sound monitoring systems makes it more challenging to design cost-effective air pollution management measures. However, this should not be a reason to delay action. There is sufficient global knowledge to begin now. As better information becomes available, reducing air pollution can become faster and more cost-effective. Moreover, sound air quality information, once placed in the public domain, can be a critical driver for public support for clean air measures and investments. Filling the information gap is therefore a critical step for ensuring sustained progress over the long term.

3. **Catalyze investments**. The investment needed to accelerate access to clean air is affordable, and policy makers could limit the need to draw on limited public resources by creating clean air markets to attract private investments. Reducing source emissions by displacing fossil fuels with renewables or improving energy efficiency are already commercially available and scalable solutions with proven business models, low risk profiles, and rapid payback periods. Public authorities can align incentive frameworks to open up substantial investment flows, including towards challenging areas such as sustainable residential heating and cooking, green mobility, and fertilizers emissions, which will also require fiscal support. Enacting clear regulations, leveraging public procurement, and removing and repurposing distortive subsidies for fossil fuels and fertilizers are priority actions for creating clean air markets.

1. Authors' calculations based on International Institute for Applied Systems Analysis (IIASA) 2024 and World Bank analysis. This number excludes deaths due to COVID-19



EXECUTIVE SUMMARY

Ambient air pollution is a critical risk to human health and future development outcomes

Ambient (outdoor) air pollution accounted for more than 5.7 million deaths globally in 2020[2] and remains a leading risk factor for premature death,[3] with corresponding economic damages estimated at between US$4.5 trillion and US$6.1 trillion a year—equivalent to between 4.7 percent and 6.5 percent of global GDP. Although there are many different types of air pollutants, particulate matter of less than 2.5 micrometers (µm) in diameter, also known as $PM_{2.5}$, is responsible for more than 90 percent of global premature deaths caused by air pollution. These particles are small enough to be breathed deep into the lungs, where they enter the bloodstream and increase the risk of cardiovascular disease, pulmonary disease, and cancer in both adults and children. The amount of $PM_{2.5}$ in ambient air is a consistent predictor of poor health outcomes around the world, with high concentrations affecting people's cognitive abilities and productivity (Lelieveld et al., 2020).

Ninety-nine percent of the world's population is exposed to unhealthy levels of air pollution that exceed World Health Organization (WHO) air quality guideline levels. However, low- and middle-income countries face the highest burden (WHO, 2022). Eighty percent of people directly exposed to unsafe average annual $PM_{2.5}$ concentrations live in low- and middle-income countries, where economic growth is often paired with a reliance on polluting technologies. About 95 percent of deaths attributable to air pollution occur in developing countries, which also carry the greatest economic toll of air pollution. In South Asia, for example, health damages from ambient air pollution exceeded the equivalent of 8.9 percent of GDP in 2020, without accounting for the implications of lost productivity on future growth.[4] Of the 2.5 billion people in the world who are exposed to hazardous $PM_{2.5}$ concentrations of more than 35 $\mu g/m^3$, most are in South Asia (1,200 million) and East Asia (660 million). A substantial portion of them live in Sub-Saharan Africa (330 million) and North Africa and the Middle East (224 million).

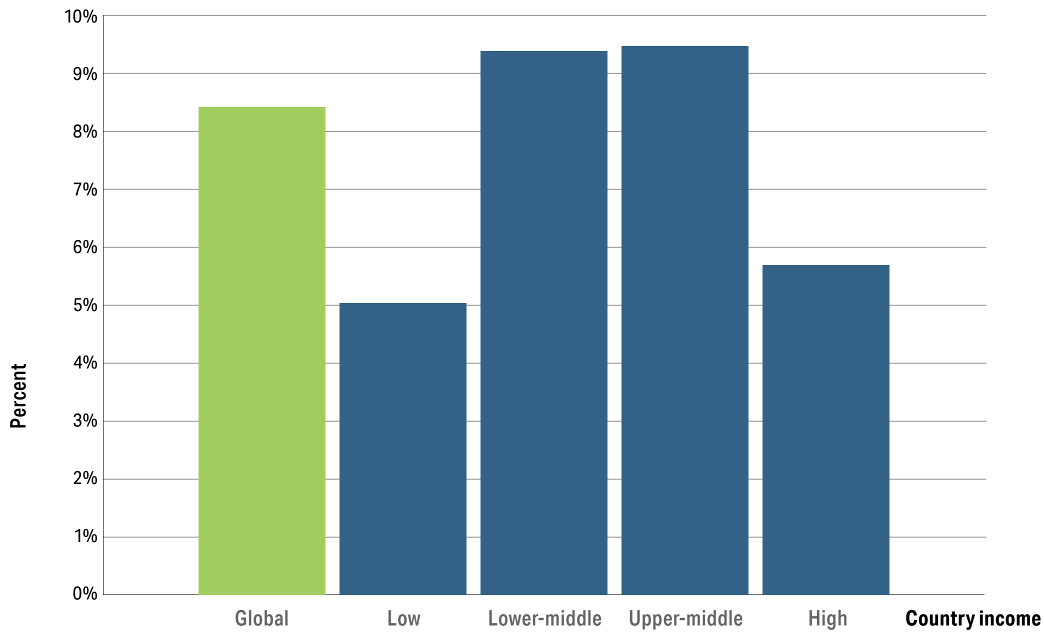
2 This number excludes deaths due to COVID-19. See Appendix D for details on the methodology for quantifying air pollution mortality and associated economic damages.

3 For more information on the health impacts of air pollution, see the State of Global Air report and website at https://www.stateofglobalair.org

4 This number excludes deaths due to COVID-19. See Appendix D for details.

Figure ES1. Air pollution-induced mortality is higher in middle-income countries

Percentage of deaths attributed to ambient particulate matter in 2020



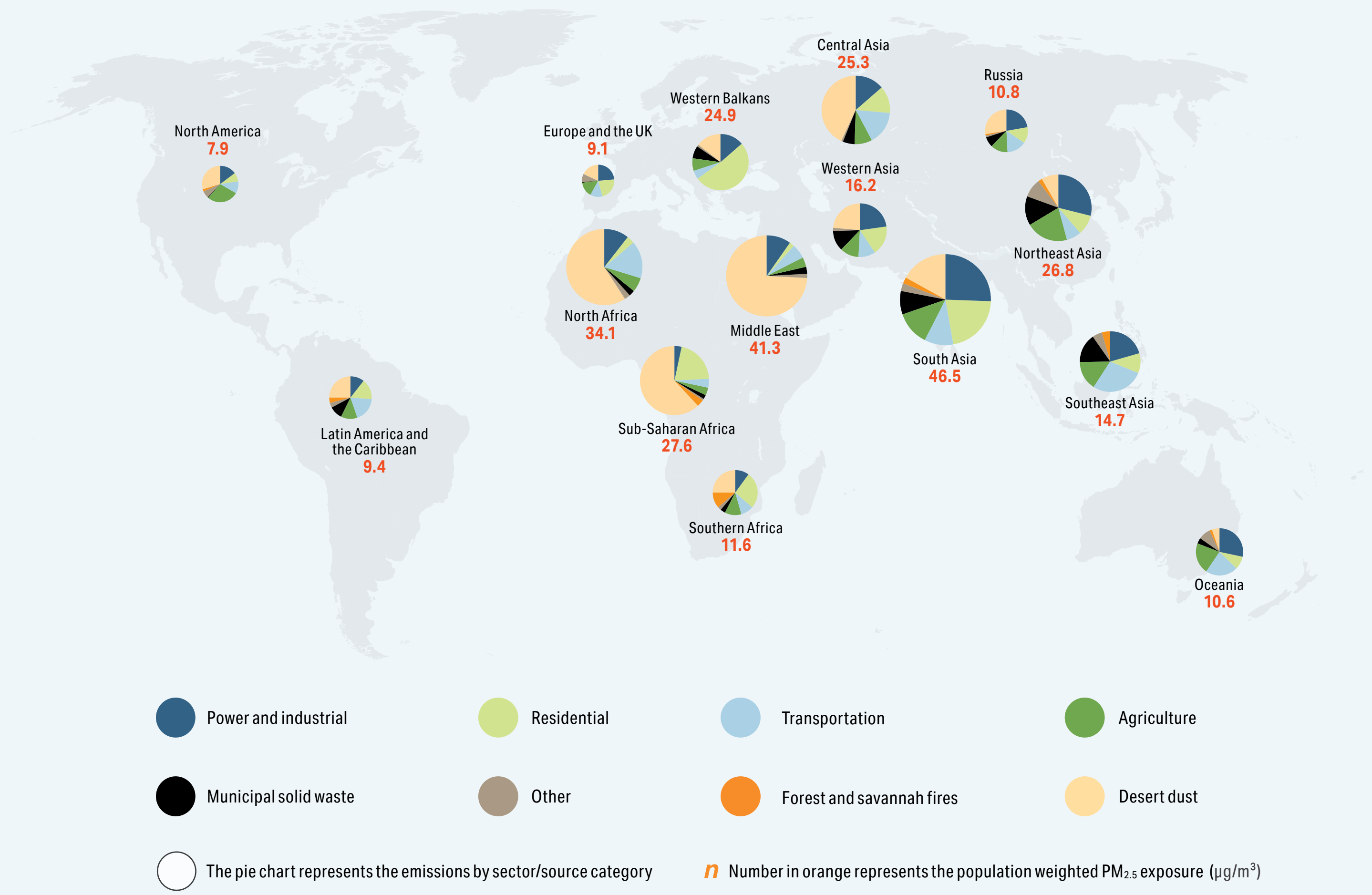
Source: Original calculations based on Burnett et al., 2018.

Poverty and inequality compound the health burden caused by being exposed to high levels of air pollution. Of the people who are exposed to unsafe levels of air pollution, 716 million live in low-income regions (especially Sub-Saharan Africa), where they survive on less than US$1.90 per day (Rentschler and Leonova, 2023). Low-paying jobs are more likely to require physical and outdoor labor and are related to increased exposure to industrial plants, transportation corridors, and other sources of pollution. These sources of pollution are also disproportionately concentrated in low-income areas. At the same time, people in such jobs and areas have limited access to quality healthcare, further increasing air pollution-related mortalities among vulnerable and low-income groups (Rentschler and Leonova, 2023). In this way, air pollution exacerbates existing socioeconomic inequalities across income brackets, with disadvantaged groups and low-income populations exposed to higher pollution levels while having fewer resources to mitigate related health impacts.

Globally, most $PM_{2.5}$ air pollution stems from anthropogenic sources. Although the dominant source of air pollution varies from region to region—with natural sources such as windblown desert dust contributing substantially to overall $PM_{2.5}$ exposure levels in the Middle East and North Africa, Sub-Saharan Africa, and Central Asia (Figure ES2)—at the global scale the majority of $PM_{2.5}$ emissions are anthropogenic. Residential heating, industry, and transport emissions are substantial in Europe and Central Asia, while residential household cooking dominates in Africa. Burning solid fuel in households is a major source of $PM_{2.5}$ exposure in many low-middle-income countries and the Western Balkans.

Figure ES2. The main sources of pollution differ widely across regions

Key emission sources for population-weighted $PM_{2.5}$ exposure in 2020, by world region



Source: Original figure for this publication.

Over the next 15 years, existing and currently planned policies are expected to lead to considerably higher, and more unevenly distributed, exposure to air pollution. By 2040, existing or planned energy and climate policies and air quality measures (the “Stated Policies scenario” described in Box ES1) are expected to curb global $PM_{2.5}$ emissions by 6 percent. However, due to economic and population growth, the number of people exposed to $PM_{2.5}$ levels exceeding 35 $\mu g/m^3$ is anticipated to increase by 15 percent, while those exposed to levels exceeding 25 $\mu g/m^3$ will increase by 21 percent. By then, global mortalities attributable to ambient air pollution are expected to increase from 5.7 million deaths in 2020 to 6.2 million deaths in 2040.[5] Most of the growth in exposure and mortality is expected to take place in Sub-Saharan Africa, Northern Africa, Central Asia, Southeast Asia, and the Middle East, where average exposure levels will increase primarily due to climbing anthropogenic emissions.

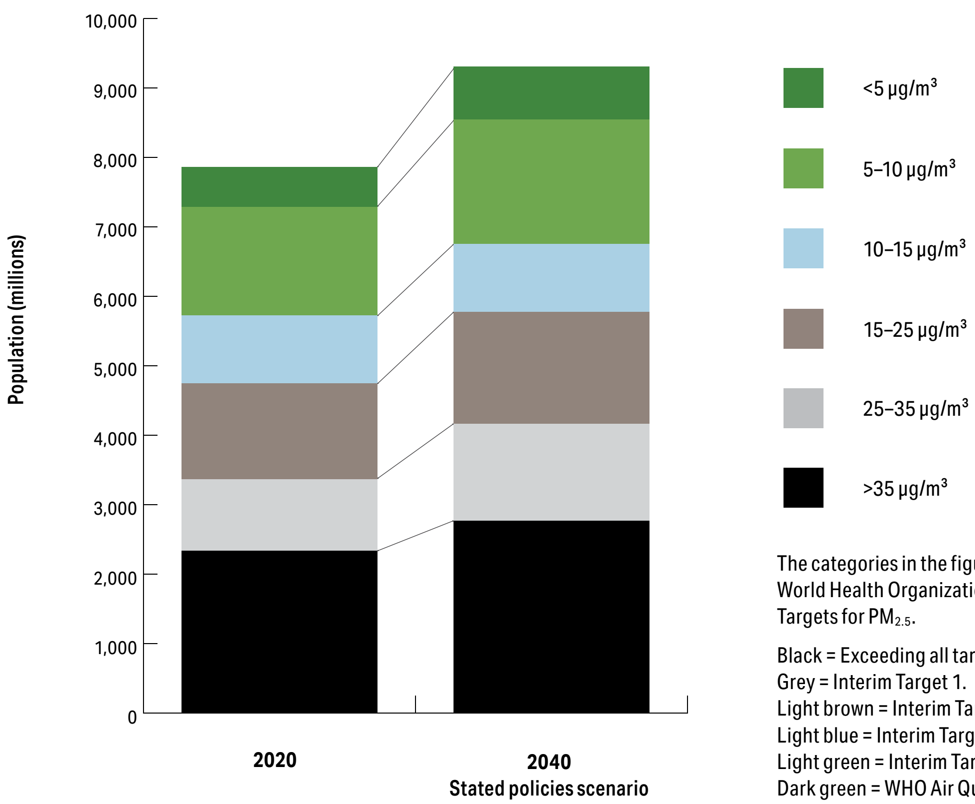
5 This number excludes deaths due to COVID-19. See Appendix D for details.

Ambitious policies could cut global exposure to air pollution in half by 2040

Implementing an integrated approach—an approach that combines conventional air quality management measures with energy and climate policies aimed at achieving other goals such as energy independence and reducing greenhouse gas emissions,[6] which often leads to using less fossil fuel and so results in lower air pollution—could halve the number of people exposed to $PM_{2.5}$ concentrations in excess of 25 µg/m^3 with significant health benefits.[7] Improvements are expected to be even more pronounced for higher $PM_{2.5}$ exposure concentrations: the number of people exposed to more than 35 µg/m^3 could decline by 60 percent, from 2.3 billion in 2020 to 0.9 billion in 2040.

Figure ES3. Despite an overall decrease in $PM_{2.5}$ concentrations, population growth will continue to drive an increase in exposure by 2040

The global population exposed to different $PM_{2.5}$ concentrations (including from natural sources) in 2020 and in 2040 under the Stated Policies scenario (projected)



The categories in the figure mirror the World Health Organization's Interim Targets for $PM_{2.5}$.

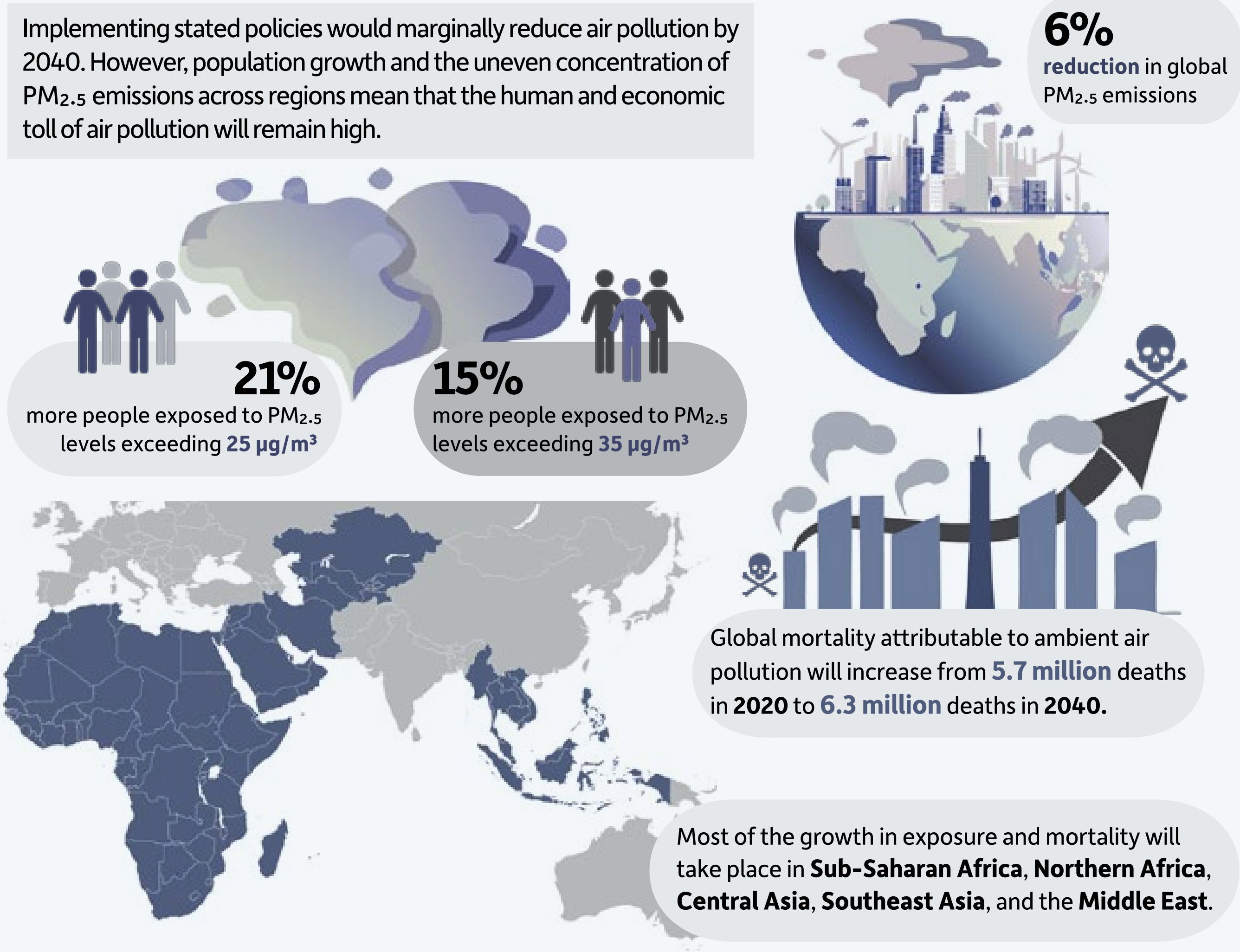
Black = Exceeding all targets.
Grey = Interim Target 1.
Light brown = Interim Target 2.
Light blue = Interim Target 3.
Light green = Interim Target 4.
Dark green = WHO Air Quality Guideline.

Source: Original figures for this publication.

6 As assumed in the World Energy Outlook's Sustainable Development scenario (IEA, 2021a). See Appendix B for examples of measures considered in the analysis.

7 See Box ES1 for a more detailed description of the Clean Air Targets considered in this report.

The toll of air pollution by 2040



Source: Original figures for this publication.

Current stated policies often neglect measures that have proven successful elsewhere, missing out on significant opportunities to further abate air pollution. Scenario modeling by the World Bank has found that applying a comprehensive package of decarbonization and air quality management (AQM) measures across all regions could halve the number of people exposed to $PM_{2.5}$ concentrations in excess of 25 µg/m^3 by 2040 and reduce the number of deaths to 4.1 million per year, in effect reducing deaths attributable to air pollution by 35 percent against the Stated Policies scenario. The highest levels of reductions, in absolute terms, would occur in Northeast Asia and lower-income regions such as South Asia and Sub-Saharan Africa (Figure ES4). Accounting for the value of averted mortality, the estimated economic benefits of such integrated policies range between US$1.9 trillion and US$2.4 trillion (in 2021 terms) over the period, equivalent to between 0.8 percent and 2.1 percent of global GDP in 2040 (see Appendix D for quantification of air pollution mortality and associated economic damages).

Integrated policies also deliver significant net climate mitigation benefits, including reductions in black carbon and methane emissions. In addition to being more cost effective, integrated

Box ES1.
Modeling scenarios and World Health Organization Air Quality Guidelines used in this report

This report uses scenario modeling to examine the effectiveness of policies and measures adopted by governments after 2005 to counteract increasing human exposure to air pollution driven by socioeconomic development and population growth.

Ultimately, the modeling exercise aims to identify policies that would achieve the following **Clean Air Targets** against a 2020 baseline:

- **In regions not affected by desert dust**: Halving the number of people that breathe air polluted by $PM_{2.5}$ from all sources in concentrations of more than 25 µg/m^3 (WHO Interim Target 2).
- **In regions affected by desert dust**: Since measures to reduce natural dust are not available in the short term, halving the number of people that breathe air polluted by $PM_{2.5}$ from anthropogenic sources at concentrations of more than the WHO guideline value of 5 µg/m^3.

The report examines the following four policy scenarios:[i]

- **Stated Policies**. This scenario assumes that low-carbon development policies (the "Stated Policies Scenario [STEP]" scenario as outlined in the International Energy Agency's World Energy Outlook 2021) and air pollution regulations and measures agreed upon by 2020 and incorporated into the International Institute for Applied Systems Analysis' GAINS model[ii] will be effectively implemented. This scenario is the "business-as-usual" scenario in this report, serving as a comparison point against which the effectiveness of other scenarios can be measured. A comparison between the Stated Policies scenario and a scenario that excluded stated policies, but still considered increases in economic activities, concluded that the Stated Policies scenario would result in a 6 percent decline in primary $PM_{2.5}$ by 2040.
- **Integrated Policies**. This scenario assumes that decarbonization policies (the "Sustainable Development Scenario" as outlined in the IEA's World Energy Outlook 2021, in which the global average temperature increase is limited to well below 2°C) and additional air pollution measures are implemented in an effective, cost-efficient manner by 2040. This scenario was found to be the most efficient and cost-effective method for achieving the Clean Air Targets.
- **Additional Climate Policies Only**. This scenario assumes the implementation of decarbonization policy measures from the IEA World Energy Outlook 2021 Sustainable Development Scenario.
- **Additional Air Quality Management Policies Only**. This scenario pursues the 2040 Clean Air Targets solely through additional conventional air quality management options (e.g., end-of-pipe emission controls).

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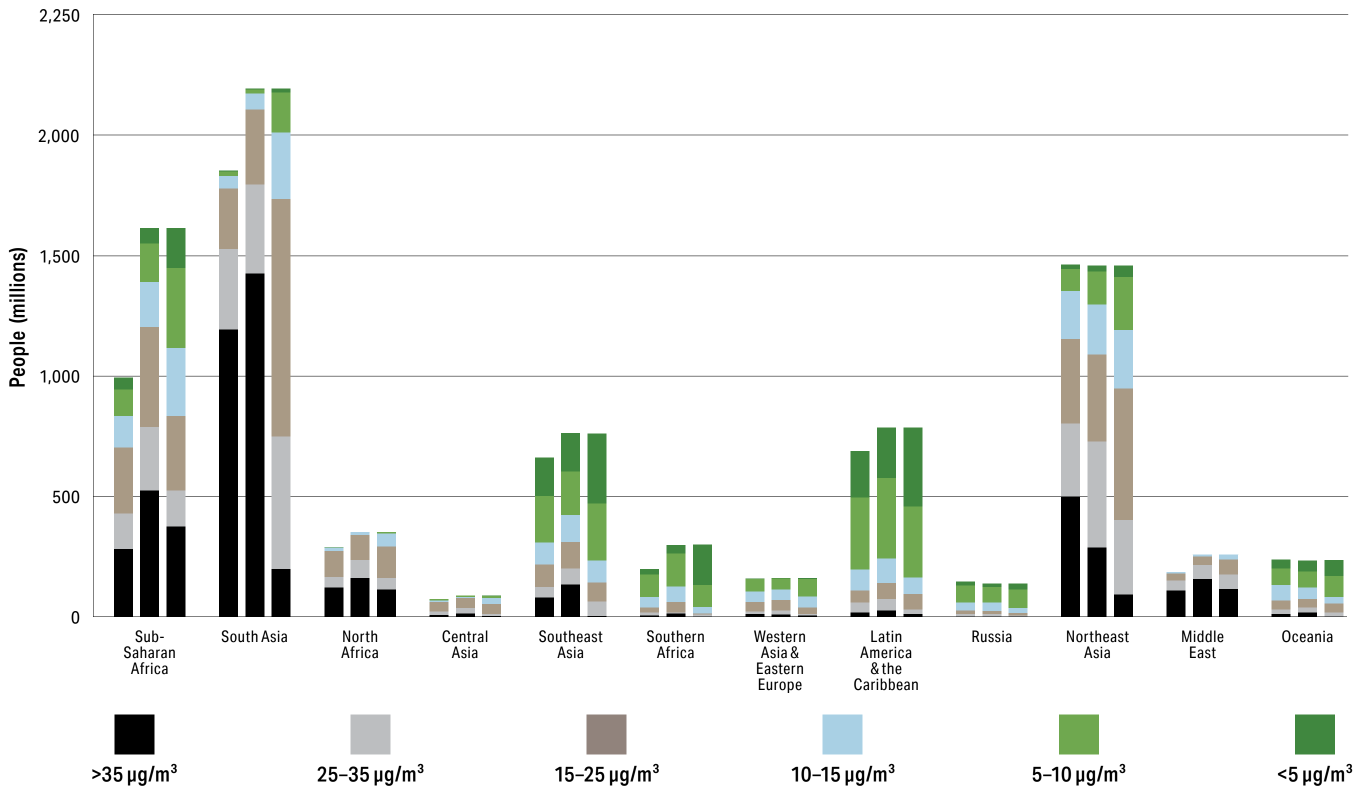
i See Appendix B for examples of measures considered in the analysis, including those considered in the Integrated Policies scenario.

ii The GAINS model provides a framework for describing the pathways of atmospheric pollution from anthropogenic driving forces to relevant health and economic impacts. For more information, see: https://iiasa.ac.at/models-tools-data/gains

Figure ES4. Low-income regions would benefit the most from implementing integrated climate/energy and air quality management policies

Number of people exposed to varying concentrations of $PM_{2.5}$ (including from natural sources) in 2020 (actual) and 2040 (projections based on Stated Policies and Integrated Policies scenarios)



This figure excludes Europe and the United Kingdom, the Western Balkans, and North America because, by 2040, if all stated policies in these three regions are implemented, the Clean Air Target (of halving the number of people exposed to pollution levels above 25 µg/m³) will have been achieved.

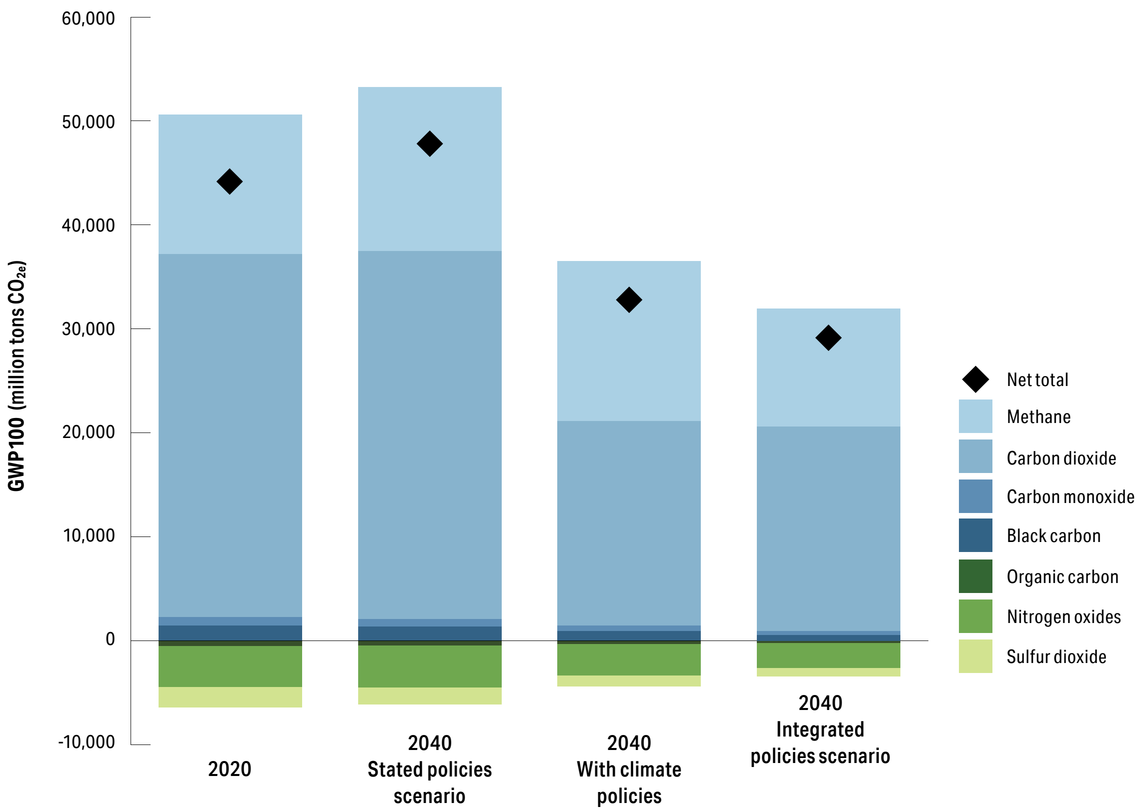
Source: Original figure for this publication.

policy packages are expected to deliver up to a 40 percent net reduction in overall global warming potential over 100 years (GWP100) compared to the Stated Policies scenario. While 80 percent of this anticipated decline stems from energy and climate policy measures, 20 percent is attributable to clean air measures, especially those that abate methane and black carbon emissions in municipal waste management, agriculture, and transport (Figures ES5 and ES6). Addressing black carbon and methane emissions early on will also help counteract the increased warming that could occur when cooling aerosols such as sulfur dioxide, nitrogen oxides, and ammonia are reduced.

Reducing global exposure to $PM_{2.5}$ in a cost-effective manner through integrated, cross-sector policies requires context-sensitive sequencing and the prioritization of specific measures. World regions differ in terms of geophysical and econo mic conditions, as well as the status of implemented policies. This creates a diversity of potential for policies and measures to mitigate air pollution across sectors. Although achieving the Clean Air Targets requires emissions to be reduced across all sectors, globally about 55 percent of exposure reductions are expected to come from residential cooking and heating (Figure ES6).

Figure ES5. Integrated policies deliver climate mitigation benefits in addition to reducing $PM_{2.5}$ exposure

Effect of reducing greenhouse gases and short-lived climate pollutants (i) under the Stated Policies scenario, (ii) with additional climate policies, and (iii) under the Integrated Policies scenario on 100-year global warming potential by 2040, compared with actual data in 2020



Source: Original elaborations based on GWP100 climate metric.

In most low- and middle-income countries, halving $PM_{2.5}$ exposure by 2040 will require efforts to reduce pollution from the residential heating and cooking sector, which directly contributes to outdoor air pollution. Solid fuel combustion in households is the largest anthropogenic source of chronic exposure to ambient $PM_{2.5}$ and other air pollutants (such as black carbon) in most low- and middle-income countries. Although solutions beyond replacing traditional stoves and burners with improved cookstoves exist, making such improvements at scale can be challenging and raise concerns about affordability, the reliability of fuel quality and supply, the replicability of results, and the need for behavioral change. However, improvements in and availability of cleaner cooking options in households, even with stove stacking (the concurrent use of multiple stoves or fuels), will improve outcomes.

Achieving universal access to modern, energy-efficient, electric residential cooking solutions—while aspirational—will take time. In the interim, air quality and health outcomes can quickly be improved by promoting a mix of cleaner solutions (such as LPG, biogas, and ethanol) along with electricity. This will probably involve expanding the use of LPG stoves and improving fuel availability, even as access to electric cooking options increases.

Measures to reduce the widespread use of biomass and coal to heat indoor spaces will be key for regions affected by long, cold winters. In Europe and Central Asia, 83 percent of space heating uses fossil fuels. Thirty percent of households in the region rely on district heating utilities, nearly all of whom use fossil fuels, with coal playing a dominant role. To improve air quality, there is therefore a need to shift to cleaner fuels, improve combustion efficiency at both the utility and home level, and implement building and home improvements at scale. As with residential cooking, solutions here revolve around improving fuel choices and enhancing energy efficiency by upgrading equipment. Both transitions will require incentives and support mechanisms to encourage consumers to adopt new technologies at scale.

The agriculture sector (especially industrial farming) is a significant source of air pollution, despite being negatively affected by it. Intensive fertilizer use, poor manure management, and the burning of crop residue, especially in Asia, contribute significantly to $PM_{2.5}$ concentrations. Fossil-fuel-powered farm equipment, irrigation pumps, and generators—especially those with poorly maintained diesel motors—also contribute to air pollution. While a range of existing technologies and practices could limit emissions from the agriculture sector, their adoption depends on farmers having the financial and technical capacities to do so. A reorientation of financial support for farmers and investments to advance agricultural knowledge and identify and deploy innovative systems would facilitate the reduction of air pollution from agricultural sources.

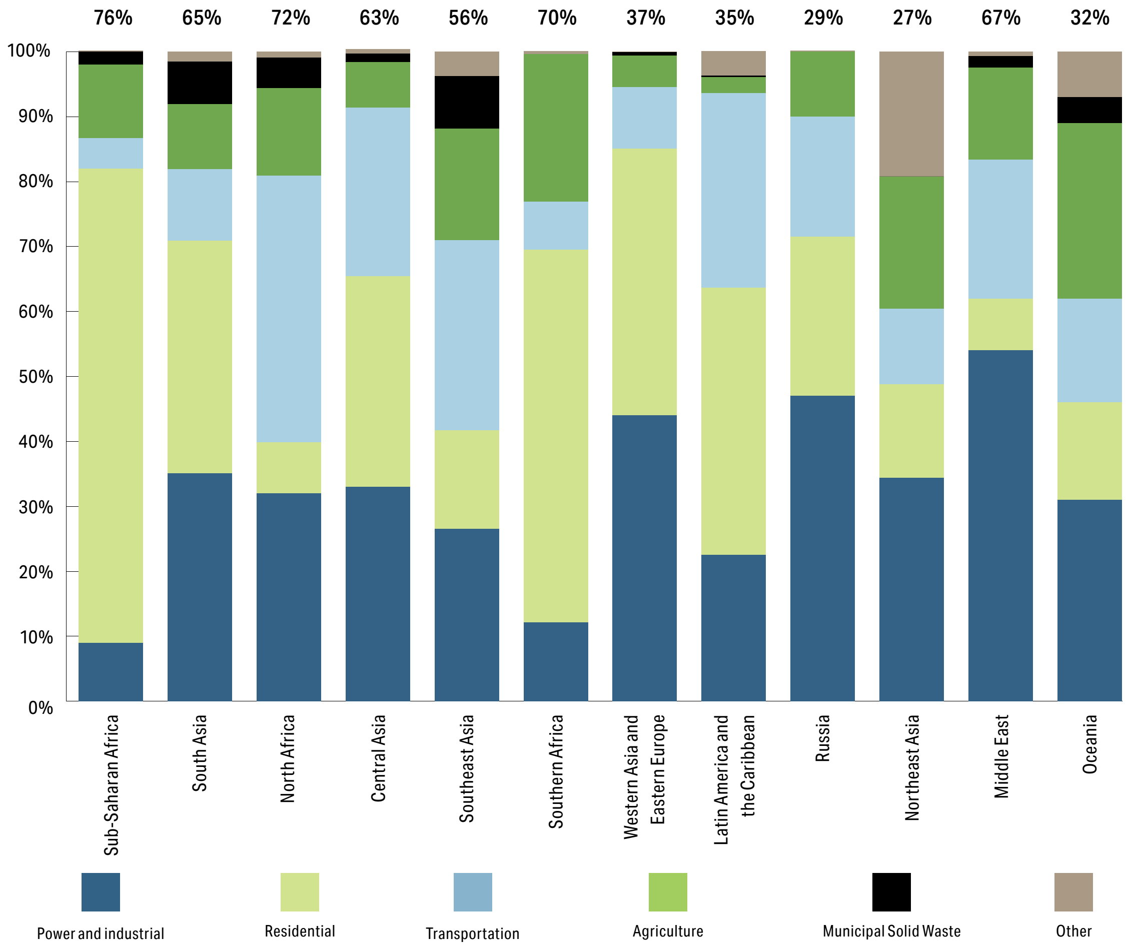
Reducing air pollution in South Asia, Northeast Asia, the Middle East, and North Africa requires decisive action in the power generation and industrial sectors. Investing in the abatement of industrial air pollution often generates economic returns and is associated with improvements in companies' competitiveness. However, market, financial, and technical support need to be tailored to countries' specific industrial and socioeconomic landscapes. Government approaches to reducing air pollution typically focus on: (i) implementing industrial air pollution regulations and emissions standards; (ii) introducing pollution-control technologies; (iii) promoting cleaner production processes; (iv) providing incentives for adopting renewable energy; and (v) establishing monitoring and enforcement mechanisms to ensure compliance.

Air pollution from the transport sector is growing in low- and middle-income countries, pointing to a need to adopt an "Avoid, Shift, Improve" approach to curb particulate emissions. The transport sector contributes significantly to $PM_{2.5}$ pollution, in addition to nitrogen oxides and sulfur oxide emissions, particularly in urban areas. Reducing the need for private travel through more efficient, compact urban development; facilitating the shift from private to public transportation; implementing urban transport management measures; and encouraging fleet renewal towards more efficient, emission-neutral vehicles are synergistic approaches to reducing air pollution from transport.

Reducing exposure from desert and soil dust will prove more challenging. Landscape restoration has a clear role to play in addressing air pollution from desert and soil dust, especially in urban areas. Filtering polluted air is one of the ecosystem services that trees and urban forests provide. However, establishing such solutions demands substantial initial investment into land as well as long-term financing to support the maintenance and preservation of urban trees and forests. Global experience shows that municipal authorities can leverage a range of financial instruments (such as public-private partnerships, tax increment financing, green bonds, and carbon finance) for such investments.

Figure ES6. Cost-effective integrated policy packages are context-specific

Sectoral breakdown of additional exposure reductions needed to achieve the Clean Air Targets through integrated policies, by region



The percentages above each bar indicates the extent of total exposure from anthropogenic sources to be reduced in each region in order to reach the 2040 Clean Air Target.

The colored segments in each bar indicate the sectors in which additional policies and measures emerge as being the most cost effective for achieving the 2040 Clean Air Targets through integrated policies.

Source: Original figure for this publication.

Cities—where both pollution and people are found in high concentrations—are important target areas for curbing air pollution. Cities in lower- and middle-income countries face the highest concentrations of $PM_{2.5}$, followed by cities in upper-middle- and low-income countries, then those in high-income countries. City governments have an important role to play in identifying and addressing sources of local air pollution such as specific industrial activities, transportation corridors with heavy traffic, and landfills. City governments are well placed to protect vulnerable local groups such as the elderly, children, outdoor workers, and residents with respiratory conditions. However, while many countries and regions still focus AQM measures on cities, the importance of effective national air quality policies and regulations that consider an airshed approach is becoming more evident.

Halving the population exposed to air pollution by 2040 is affordable and makes sound economic sense, but needs additional financing

Investing in clean air makes economic sense. With the health and related economic toll of air pollution expected to increase—especially in developing regions such as South Asia, which lost 10 percent of its regional GDP in 2019 due to morbidity and mortality-related losses—the economic case for clean air investments is strong. Across all geographies, air pollution abatement measures yield positive returns. In Delhi, for instance, the value of implementing air pollution abatements exceeds costs by 2 to 3.6 times, while in the United States, every dollar spent on air pollution controls yields about US$30 in net economic benefits.

Achieving the Clean Air Targets[8] is within reach by combining public and private resources. Halving the population exposed to $PM_{2.5}$ levels above 25μg/m^3 by 2040 through integrated climate/energy and air quality measures will require additional cumulative investments of US$3.2 trillion globally, entailing an estimated increase in yearly global investments in AQM from US$8.5 billion in 2020 to US$13.9 billion in 2040. While substantial in absolute terms, these investments seem more manageable once considered as a share of global GDP, which sees investments fall from 0.95 percent of global GDP in 2020 to only 0.49 percent by 2040. Despite this decline, governments will still need to find innovative ways to leverage greater private investment. While public sector resources are foundational in the air quality financing landscape—by providing enablers such as policies, standards, incentives, and supporting infrastructure—they are largely inadequate in most world regions. This is especially true in low- and middle-income countries, where already strained fiscal capacities will continue limiting the allocation of public resources to curbing rising pollution levels.

Creating an enabling environment for private sector financing of air pollution measures could address the financing gap. The private sector's involvement in air quality financing continues to be held back by weak policies with insufficient enforcement, uncertain returns, complex revenue models, and the perception of risk. However, global experience shows that it is possible to mobilize private capital for air quality improvements by enabling reforms that revise distortive policies (such as subsidies for environmentally harmful fossil fuels), address market failures (through pollution regulations and pricing), and create incentives (such as revenue-guarantee schemes and risk-sharing mechanisms). Subsidies, tax incentives, and other forms of fiscal support will remain central to helping households, farmers, and companies address the upfront investment costs of transitioning to cleaner technologies, particularly in sectors characterized by dispersed sources of air pollution.

Development finance institutions (DFIs) can deploy non-traditional financial instruments to attract private sector investment. At only 5.9 percent of total bilateral and multilateral aid (CPI, 2024), international development funding to address air pollution is inadequate to address the problem. In addition to better aligning grant and concessional resources with this development priority, DFIs can deploy innovative financing instruments to attract private sector investment. These include guarantees, risk-mitigation tools, and bespoke financing mechanisms (such as sustainability-linked loans, green bonds, results-based financing, blended finance approaches, and impact bonds), which are underutilized

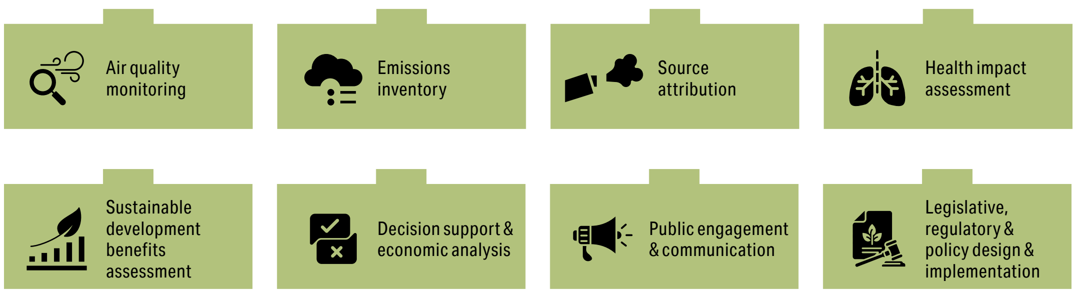
8 As set out in Box ES1.

in the air quality financing landscape. Supporting the creation of stable regulatory environments with clear standards and pollution pricing frameworks should also feature strongly in DFI objectives.

Curbing air pollution exposure requires stronger institutions

Designing and implementing cost-effective AQM systems can be complex, yet many jurisdictions have succeeded. The core building blocks of successful AQM systems include a sound legal and regulatory framework, strong reliance on scientific information to identify pollution sources, strong monitoring systems allowing for iterative evaluation and assessment, and continued communication efforts to raise public awareness (Figure ES7). Overall, however, AQM systems across all regions remain underdeveloped or ineffective at addressing the challenge of rising air pollution exposure. In particular, monitoring networks remain underresourced.

Figure ES7. The building blocks of effective air quality management systems

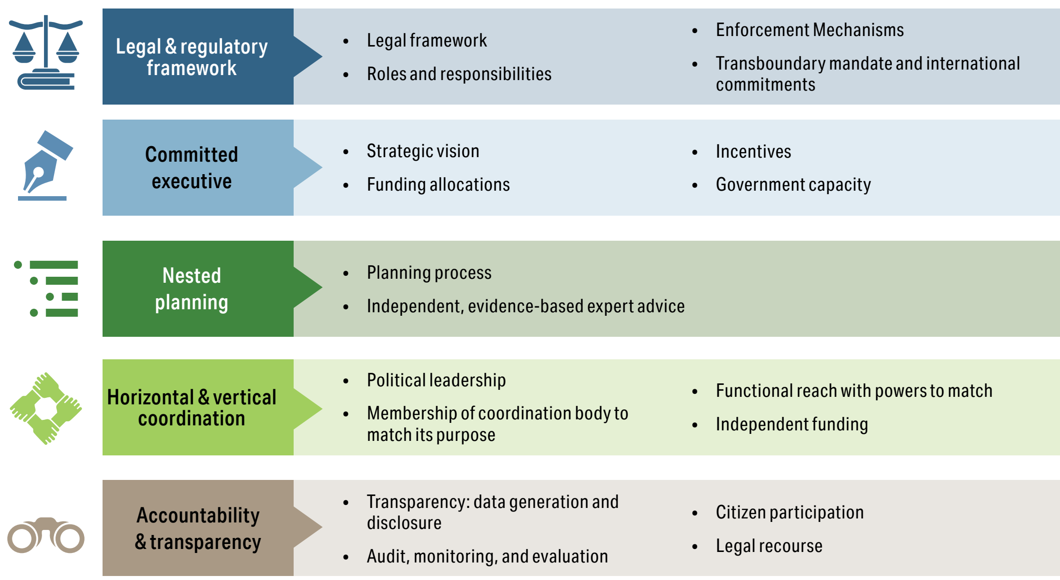


Source: Own elaboration and AOMx (2024).

Effective AQM systems also need to consider the role of institutional and governance cross-cutting mechanisms and processes. To that end, a coherent framework has been developed to assess the institutional capacity for effective and efficient AQM. This framework consists of 18 components organized around five attributes and includes a set of guidance questions to assess formal institutions and formal and informal behaviors. Emerging evidence from countries at various maturity levels of airshed planning and management suggests that the framework can be used to develop recommendations on the following governance and institutional attributes: (i) a legal and regulatory framework, (ii) a committed executive, (iii) nested planning, (iv) horizontal and vertical coordination, and (v) accountability and transparency (Figure ES8). Changes to formal arrangements are critical, but ultimately public sector management reform is about changing the informal behaviors of agents within the public sector. Therefore, the framework identifies both formal and informal agent behaviors. The framework favors organizational and institutional function over form, meaning that what matters is how institutional mechanisms fulfill their intended function, rather than whether their appearance is appropriate.

Effective AQM calls for dedicated managers, well articulated institutional arrangements, and a commitment to accountability and transparency. Successful air pollution abatement programs are built on a foundation of technical capacity and adequate laws. They are also frequently backed by high-level government officials who champion air quality and decarbonization policies by pursuing clear, long-term agendas with well-defined goals. Clean air policies and investment planning are nested within the national and subnational tiers of government, allowing for horizontal and vertical

Figure ES8. Governance and institutional framework for assessing air quality management systems



Source: World Bank, 2025.

coordination to address local and transboundary pollution. In addition, their air quality monitoring systems are robust, allowing for transparent access to real-time, reliable data. This enables citizen engagement and strengthens government accountability.

Policy integration requires eliminating divisions between climate/energy and air quality objectives. Integrating AQM and climate mitigation would maximize synergies and enable the efficient use of resources. Fiscal policy is a case in point. Governments often use subsidies and pricing instruments (such as taxes and fees) to incentivize greenhouse gas abatement and air pollution reductions across sectors. However, these instruments are usually implemented independent of each other, without considering possible synergies and co-benefits—or potential counterproductive impacts. For example, introducing an SO_2 tax would discourage the use of coal and deliver both clean air and climate mitigation gains. However, efforts to impose pollution taxes or otherwise eliminate fossil fuel subsidies to reduce greenhouse gas emissions need to be carefully crafted to avoid shifting the cost burden from businesses and fossil-fuel companies to cities, towns, and households—which could result in people reverting to heating their homes and cooking with wood or biomass, with detrimental consequences for air quality.

Geographically spread, diverse pollution sources and scales of exposure make cooperation across institutional boundaries a prerequisite for curbing air pollution. Municipal-level interventions are crucial for addressing key air pollution sources within a city's boundaries but may be able to address only a fraction of the pollution experienced by city residents. Policies often seek to treat pollution generated within a specific geographic area but fail to address transfers of pollution into (or outside of) its boundaries. An airshed approach could prevent this problem. Already successful in Europe through the United Nations Economic Commission for Europe's Convention on Long-Range Transboundary Air Pollution, the airshed concept can be used in any region and is, with World Bank support, already gaining momentum across several jurisdictions in the Indo-Gangetic Plain. Box ES2 highlights the key interventions across different jurisdictions in this region to reduce average population-weighted exposure to $PM_{2.5}$ of 35 $\mu g/m^3$ by 2035.

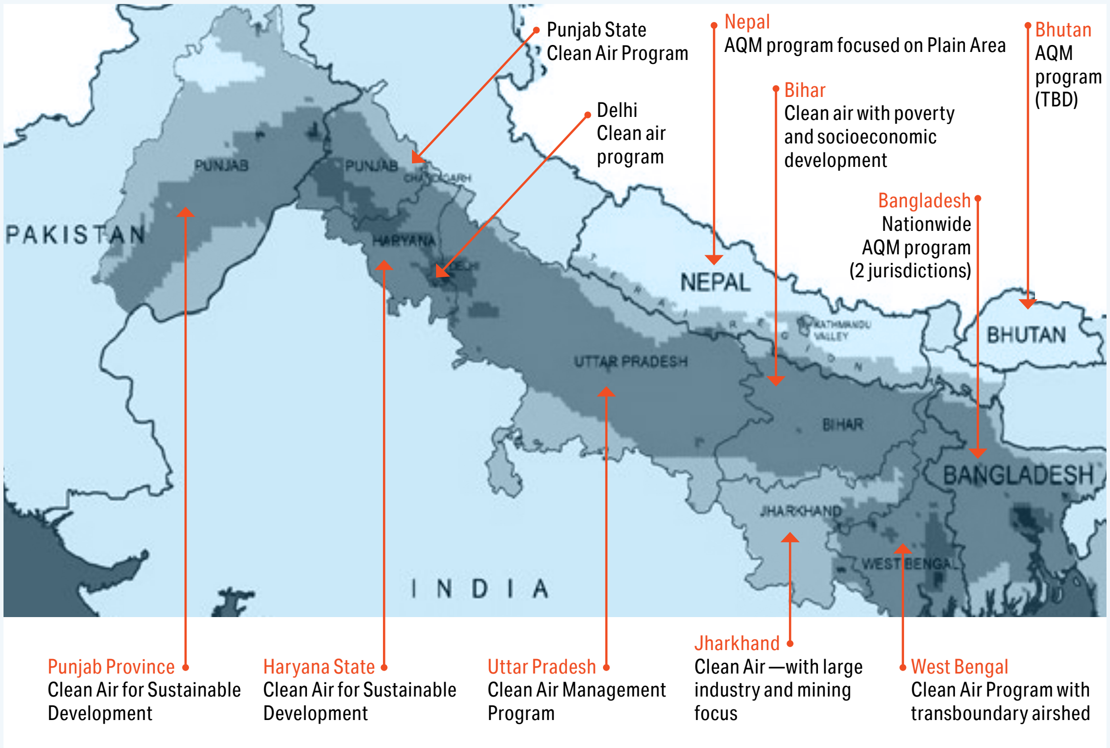
Box ES2. Key interventions in different parts of the Indo-Gangetic Plain and Himalayan Foothills region

Supporting the Indo-Gangetic Plain and Himalayan Foothills region to reach an average population-weighted exposure for $PM_{2.5}$ of 35 µg/m³ by 2035 ("35-by-35" goal)

To support achievement of this "35-by-35" goal in the Indo-Gangetic Plain and Himalayan Foothills (IGP-HF) region, the World Bank, in collaboration with other development partners, are developing an AQM collaboration program to provide lending and technical assistance to each jurisdiction within the region (Figure ES9).

Figure ES9. The air quality monitoring program in the Indo-Gangetic Plain focuses on 12 jurisdictions

Indo-Gangetic Plain and Himalayan Foothills collaboration: An airshed approach to air quality management*



Source: Original figure for this publication.

Depending on the air pollution situation in each jurisdiction, each project focuses on three result areas:

- **Institutional strengthening and AQM planning tools.** This result area focuses on establishing effective AQM institutions that can implement advanced ambient emission monitoring networks and developing operational planning and decision-support systems.

- **Advanced technologies and practices in the sectors contributing to most air pollution.** This result area focuses on implementing innovative solutions for industry, transport, clean cooking, waste management, and agriculture (such as management of livestock manure and crop-residue burning).

- **Enhance AQM collaboration between IGP-HF jurisdictions.** This result area focuses on ensuring that all IGP-HF jurisdiction oncentrations in each jurisdiction are caused by emission sources in contiguous or other neighboring jurisdictions).

Through the implementation of AQM projects within each jurisdiction, larger-scale government programs within each jurisdiction will be supported to enable each jurisdiction, as well as the overall region, to reach the "35-by-35" target.

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* The Haryana, Uttar Pradesh, Punjab Province, Bangladesh, and Nepal programmes are at the preparation stage. The other programs are at the scoping stage.

Three priorities for clean air

Halving global exposure to $PM_{2.5}$ air pollution is within reach. The health and economic impacts of increasing air pollution levels can no longer be neglected. The good news is that addressing the problem is technically feasible and financially affordable. Policy makers can ensure that clear air remains the foundation of healthy, prosperous, and productive communities by focusing on strengthening institutions, leveraging information, and catalyzing investments. These priorities apply to all geographies and jurisdictions, regardless of their current air pollution status. They do not require technical breakthroughs, incur prohibitive economic costs, or demand excessive financing. They do, however, require political will, a long-term vision rooted in short- to long-term planning, and a capacity to rally multiple stakeholders around the promise of cleaner air.

1. STRENGTHEN INSTITUTIONS

Countries with a successful track record in curbing air pollution have placed clean air at the center of the government's economic and welfare agenda. In countries such as China and Mexico, clean air outcomes have become an explicit public policy goal, championed by high-level officials and endorsed across all levels of government. Policy is set within a clear long-term vision and backed by a goal-oriented strategy grounded in fiscally consistent expenditure frameworks to ensure that clean air objectives and targets are reflected in multi-annual budgets. Fully committed executives show strong leadership. They are supported by technical teams with funded mandates, and they implement AQM policies by rallying government stakeholders, businesses, and citizens around the common cause of clean air. The first step towards strengthened institutions is to develop a strategic vision that can be carried by core government agencies while high-level government champions shape medium-term plans that include clear goals, enunciate functions, and clarify lines of accountability between government agencies.

Tackling the multisectoral nature of air pollution requires a whole-of-government approach and coherent policies. Effective institutional mechanisms for AQM call for a multisectoral policy response that is integrated with other policy objectives. Such policies typically focus on regulatory frameworks and are supported by national standards for ambient air quality, sectoral pollution controls (emissions and technology standards), and market instruments that comprehensively address air quality emission sources (for example, tradable permits and environmental fees, taxes, and subsidies). Countries rely on different mechanisms to promote clean air actions across institutional boundaries, but these mechanisms ultimately need to be embedded in legal frameworks to ensure accountability. These mechanisms often revolve around high-level working groups that contain representatives from different ministries, technical experts, and environmental and civic groups, and report on air quality trends and actions to the president or prime minister's office. Single-sector approaches remain ineffective; collaboration between ministries, provincial entities, and local bodies—backed by adequate authority and human and budgetary resources—is essential. Establishing a high-level, government-wide coordination body is an immediately actionable measure to enhance policy coherence. Global experience shows that, to be effective, these mechanisms have to be "owned" by a core agency (such as the prime minister or president's office) and tasked with shaping and enforcing a whole-of-government approach to implementing strategies and investments.

Empowering subnational governments can lead to effective airshed approaches. Successful experiences in shifting towards airshed planning are characterized by: (i) strong subnational government coordination and accountability for collaboration, (ii) enhanced public access to monitoring and emissions data, and (iii) strong support from the central government, including targeted incentives to incentivize the coordination of subnational government. Implementing an airshed approach can be hindered by the need for collaboration across municipal and national boundaries, especially when the municipalities that produce the pollution have few or no incentives to take action. Action at airshed level also takes time to see results. Central governments need to create an incentive framework for subnational governments' action. In addition to regulatory changes, the deployment of central government transfers to subregional governments—with grants being partly conditional on the achievement of results with a view to incentivizing administrative capacity and investments, as well as clean technology adoption—is a key step towards this goal.

2. LEVERAGE INFORMATION

Effective AQM systems and policies are grounded in sound monitoring systems that support both the identification of pollution sources (and their impacts) and the design of cost-effective measures based on scientific evidence. More governments monitor air quality today than ever before, but large gaps still exist. For example, the number of monitoring stations across all of Africa is only double that of the city of Paris. New technologies such as remote sensing and low-cost sensors could—despite being less robust than regulatory-grade ground-level monitors—present an opportunity to rapidly achieve adequate monitoring coverage and more granular data. The data received from such technologies could be used in the design, implementation, enforcement, and assessment of the effectiveness of pollution-control policies. Air quality monitoring, management, laboratory, and analytical capacities could be developed at scale through regional "communities of practice" that could share both technical infrastructure and human resources. Such an approach would help counteract capacity constraints in developing countries. The first actionable step here focuses on identifying and mapping air quality monitoring gaps and defining related investment needs, potential sources of financing, and regional partners to fill these gaps.

Define and pursue synergies between decarbonization and clean air goals. Identifying and taking early action on sectors that emit large amounts of black carbon will help to prioritize AQM measures that would both reduce $PM_{2.5}$ and offset the warming that results from the co-reduction of "cooling" aerosol components (such as sulfates and nitrates). A focus on methane-rich sources (such as livestock, waste, and rice agriculture) would similarly provide near-term climate benefits while supporting sectoral reforms relevant to air pollution. The first step to pursue synergies between decarbonization and clean air policies revolve around preparing integrated AQM and mitigation plans based on robust inventory and source-apportionment studies. Focusing first on black-carbon-rich sectors for AQM reductions would also maximize the economic and health co-benefits of such measures.

Sharing air quality information and engaging citizens provides the foundation for impactful and continued clean air action. Although clean air is foundational to a healthy and productive life, only half of the world's governments publicly share air quality data. Openly and transparently sharing air quality information—including pollution dynamics, current mitigation measures, and constraints to achieving air quality goals—enables communities to demand that their governments take sustained action to ensure clean air while also providing critical feedback to policy makers on the impacts of existing policies (Grainger and Schreiber, 2019; Barwick et al., 2023). Placing air quality information in the public domain and supporting civil society groups advocating for clean air action is an inexpensive yet effective way to promote sustained air quality improvements at scale.

3. CATALYZE INVESTMENTS

To catalyze investments, countries could leverage public funding and implement regulations to open clean air technology markets to create attractive environments for private sector financing. Investments in clean air are affordable and pay off in both the short and the long term. Investments to reduce source emissions (such as those that aim to displace fossil fuels with renewables or to enhance energy efficiency in public and industrial buildings) are commercially available and scalable, with proven business models, low risk profiles, and rapid payback periods. More challenging measures that require public support—such as increasing the use of sustainable residential heating and cooking, rolling out green mobility, and reducing emissions from fertilizers and the burning of agricultural residues—are also cost-effective once the health, welfare, and productivity gains expected to accrue in the long term are considered. First-order measures to catalyze private investments include: (i) embedding a timeframe for achieving clean air objectives in policy to provide clear signals to economic actors and investors in the short, medium, and long term; (ii) enacting clear regulatory frameworks that mandate both emission limits and concentration-reduction improvements across geographies; (iii) improving monitoring networks to support the regulatory frameworks; and (iv) initiating public procurement to create and expand markets for clean air technologies.

Removing and repurposing environmentally harmful subsidies for fossil fuels is central to catalyzing private investments in clean air. Subsidies for fossil fuels and fertilizers create market distortions that reduce the cost effectiveness and increase the payback times of clean air investments, ultimately limiting incentives towards action. In 2022, US$7 trillion (7.1 percent of global GDP) was spent to support the use of fossil fuels. In addition to directly encouraging air pollution and its known externalities—chronic diseases, premature deaths, and productivity losses—subsidies for coal and heavy oil also make clean air interventions less effective: once coal for domestic heating is subsidized, consumers have less incentive to comply with limits or draw on fiscal support programs that aim to incentivize a switch to cleaner sources. When it comes to residential heating and cooking, switching to cleaner transitional fuels such as natural gas and LPG should also be incentivized from both an air pollution abatement and a climate change mitigation perspective. In addition to directly reducing $PM_{2.5}$ concentrations and indirectly supporting regulatory and fiscal measures that support clean air, phasing out counterproductive subsidies also results in fiscal savings. Similarly, subsidies for fertilizers lead to their overuse, resulting in further investment being needed to support soil-health programs. Because fossil fuel subsidies are generally poorly targeted, their phase out can disproportionately affect the most vulnerable in society, such as poor households (who typically spend more of their budget on energy costs) and small farms (which do not typically have easy access to alternatives to fuels or fertilizers). Assessing these distributional effects and implementing compensatory measures is the first actionable step that governments can take to mitigate the social impacts and increase the acceptability of policies to phase out subsidies. Fiscal expenditures previously absorbed by subsidies can then be directed towards addressing social and competitiveness tradeoffs through, for example, targeted transfers to vulnerable populations exposed to fuel-cost increases; incentives to encourage small and medium-sized enterprises to adopt more energy efficient technologies; and support for farmers to encourage them to minimize fertilizers and adopt more sustainable farming approaches.

The expected benefits of such actions—in terms of economic returns, financial savings, and lives saved—build an unequivocal case for stepped-up action on air pollution and make the clean air agenda a clear policy priority for the next decade.

1 INTRODUCTION

Air pollution is a global issue that threatens human health and development

While the World Health Organization (WHO) provides guideline targets for common pollutants, underlying studies show that more than a third of the world's population is regularly exposed to hazardous levels of fine particulate matter exceeding 35 µg/m^3, with consequences for human mortality, morbidity, and overall health.

This report compares the effectiveness of implementing current AQM policies against implementing a suite of integrated sectoral policies that blend air quality measures with climate/energy policies (Box 1.2). It is important to note that while the report's main focus is on ambient (outdoor) air pollution caused by fine particulate matter with a diameter of 2.5 micrometers (µm) or less ($PM_{2.5}$), there are also other relevant types of air pollution that have impacts on human and environmental health such as nitrogen dioxide, ground-level ozone, and air toxics.

MAIN MESSAGES IN THIS SECTION

- Air pollution poses health and economic challenges across all regions in the world.
- Particulate matter of 2.5 µm ($PM_{2.5}$) is the primary factor in air pollution-induced human morbidity and mortality across the globe.
- Current air quality management (AQM) policies are not sufficient to effectively reduce $PM_{2.5}$ exposure to within World Health Organization guidelines by 2040.
- An integrated approach—one that combines conventional AQM measures with energy and climate policies that are designed to achieve other goals, such as energy independence or reducing greenhouse gas emissions assumed in the International Energy Agency's 2021 World Energy Outlook sustainable development scenario—could reduce the population exposed to $PM_{2.5}$ concentrations above 25 µg/m^3 by half and the deaths attributable to air pollution by 35 percent, with concomitant global economic benefits.
- Integrated policies could also provide significant climate change mitigation gains, while costing less to implement than climate change or air quality policies implemented independently.

1.1 THE GLOBAL COST OF AMBIENT AIR POLLUTION

Ambient air pollution is taking an increasing health and economic toll, especially in lower-income countries.

Poor outdoor air quality is now the second-leading cause of premature death worldwide after cardiovascular disease, contributing to 5.7 million deaths—95 percent of which occurred in developing countries—in 2020.[9] In many areas of the world, the problem is worsening. A strong body of evidence shows how even low concentrations of air pollution can negatively affect human health, placing major strain on healthcare systems and leading to detrimental social and economic effects. Concerningly, 91 percent of the global population live in areas that exceed the WHO's Air Quality Guidelines (Box 1.1).

The health damages caused by outdoor air pollution are estimated at US$6 trillion a year, equivalent to 4.6 percent of global gross domestic product (GDP), with the toll being highest in middle-income countries. For example, the annual cost of health damage from $PM_{2.5}$ in South Asia was equivalent to 10.3 percent of GDP in 2019 (World Bank, 2022). Air pollution also contributes to almost 231 million disability-adjusted life years annually, adding to the global burden of disease. While household air pollution continues to cause a higher share of deaths in Africa, South Asia, and low-income countries compared to the global average while also contributing to ambient air pollution, recent trends point to increasing risks and costs of ambient air pollution in developing countries of all income levels. At the same time, household air pollution contributes to ambient air pollution, and addressing it provides an opportunity to reduce ambient air pollution as well.

Exposure to fine particulate matter is the key driver of air pollution-induced morbidity and mortality. A robust scientific body of evidence on health impacts from air pollution has demonstrated the strong link between short- and long-term exposure to $PM_{2.5}$[10] and mortality, with more than 90 percent of the total burden of disease from air pollution being attributable to $PM_{2.5}$ exposure (Figure 1.1). Exposure to $PM_{2.5}$ causes cardiovascular and respiratory diseases, leading to conditions such as such as ischemic heart disease, strokes, lung cancer, chronic obstructive pulmonary disease, and Type 2 diabetes mellitus (WHO, 2024).

9 This number excludes deaths due to COVID-19. Appendix D provides details of methodology for quantifying air pollution mortality and associated economic damages

10 Including secondary particles.

Box 1.1. World Health Organization Air Quality Guidelines

The WHO provides global air quality guidelines for acute and long-term exposure to particulate matter of different sizes ($PM_{2.5}$ and PM_{10}), ozone, nitrogen dioxide, sulfur dioxide, and carbon monoxide. The most recent update was issued in 2021 (WHO, 2021).

While not being legally binding, the guidelines provide WHO member states with an evidence-based tool to inform legislation and policy. Ultimately, the guidelines aim to steer clean air policies and decrease the enormous health burden resulting from exposure to air pollution worldwide.

The WHO Air Quality Guidelines and Interim Targets for annual $PM_{2.5}$ exposures are as follows::

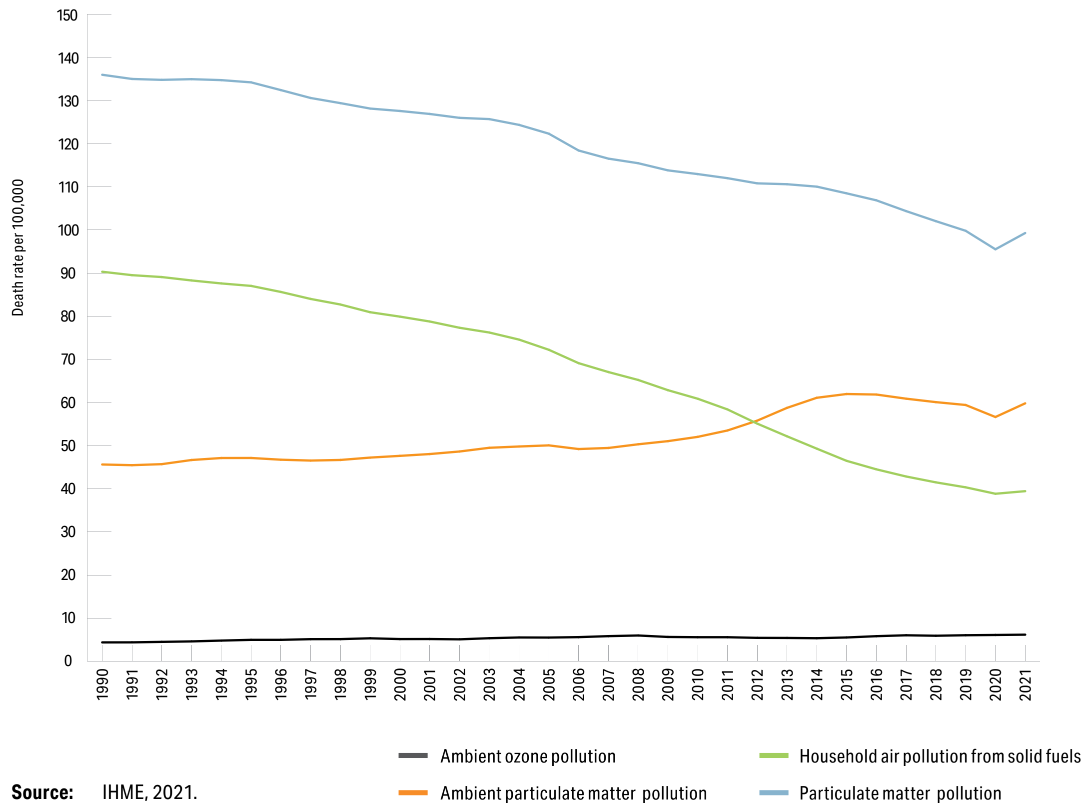
- Interim Target 1: 35 micrograms per cubic meter ($\mu g/m^3$)
- Interim Target 2: 25 $\mu g/m^3$
- Interim Target 3: 15 $\mu g/m^3$
- Interim Target 4: 10 $\mu g/m^3$
- Air Quality Guidelines: 5 $\mu g/m^3$ or less.

The WHO Guidelines refer to total $PM_{2.5}$ concentrations without differentiating between the toxicity of different substances of $PM_{2.5}$. The Guidelines and Interim Targets explicitly include exposure to $PM_{2.5}$ from natural sources such as soil and desert dust. Importantly, no "safe" value for $PM_{2.5}$ exposure has been identified. Any reduction of population exposure will lead to additional health impacts, even at very low concentrations.

The full guidelines are available at:
https://www.who.int/publications/i/item/9789240034228

Figure 1.1. The death toll of ambient air pollution continues to rise, while death rates from household air pollution decrease

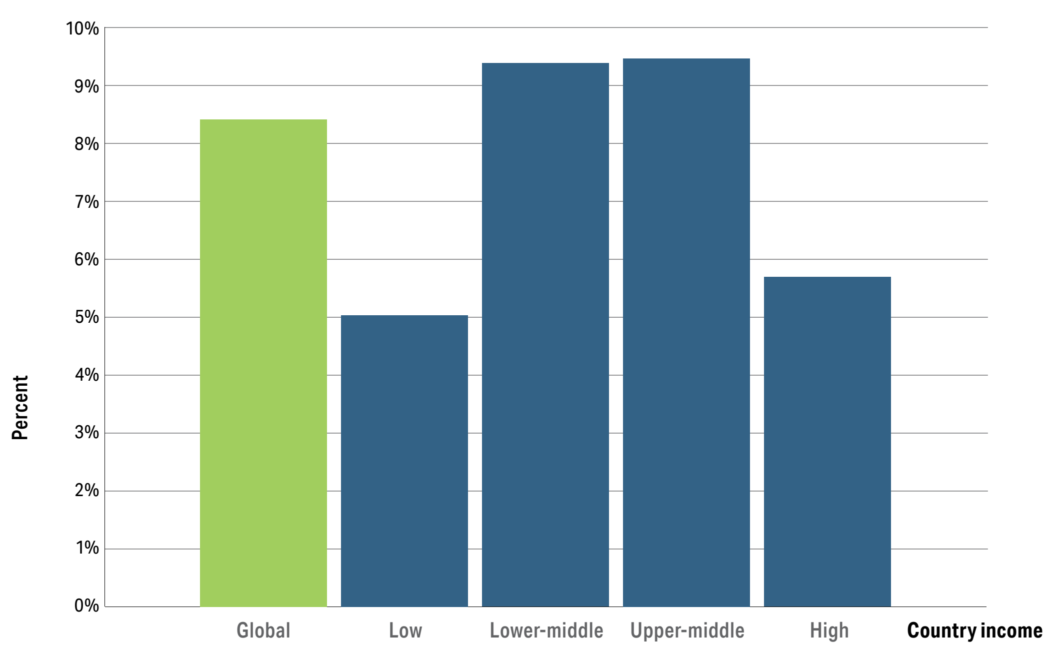
Death rates attributed to ambient, household, and ozone air pollution, 1990–2020



Source: IHME, 2021.

Figure 1.2. Air pollution induced mortality is higher in middle income countries

Percentage of deaths attributed to ambient particulate matter in 2021



Source: Original calculations based on Burnett et al., 2018.

Nearly half of the global population is exposed to levels of $PM_{2.5}$ concentrations above 25 micrograms per cubic meter (µg/m^3). The WHO's Global Air Quality Guideline specifies an annual mean $PM_{2.5}$ concentration of less than 5 µg/m^3 (WHO, 2021). In 2020, only a small portion of the global population (mainly in remote areas in Latin America, Southeast Asia, and Oceania) breathed air that complied with this guideline (Figure 1.3).[11] In the same year, about 45 percent of the global population breathed air that exceeded 25 µg/m^3 (WHO Interim Target 2), and almost a third of the global population was exposed to air with $PM_{2.5}$ concentrations of more than 35 µg/m^3 (WHO Interim Target 1). Exposure to concentrations exceeding 25 µg/m^3 affects 80 percent of people in South Asia and the Middle East, 60 percent in China and Mongolia, 54 percent in Northern Africa, and 48 percent in Sub-Saharan Africa.

A wide range of economic activities are responsible for $PM_{2.5}$ emissions. $PM_{2.5}$ can be either directly emitted (primary PM) or chemically formed in the atmosphere from precursor emissions such as sulfur dioxide (SO_2), nitrogen oxides, and ammonia (secondary PM). Primary $PM_{2.5}$ originates from a wide range of sources, including fossil fuel combustion, open-fire cooking, industrial processes, the burning of agricultural residues, waste, and road and construction dust. In some regions, natural sources such as windblown desert dust also contribute significantly to $PM_{2.5}$. Secondary $PM_{2.5}$, which makes up about one-third of total $PM_{2.5}$,[12] forms downwind of emission locations through the chemical transformation of gases such as nitrogen oxides, SO_2, and volatile organic compounds emitted when fuel burns or solvents evaporate. Ammonia, which is emitted by agricultural sources such as nitrogen fertilizer and when livestock manure is stored and used, combines with nitrogen oxides and sulfur dioxide to form ammonium nitrate and ammonium sulfate $PM_{2.5}$ particles.

The sources of $PM_{2.5}$ exposure vary widely across regions. While heating, industry, and transport emissions are important sources in Europe and Central Asia, cooking and natural sources (such as desert dust) dominate in Africa, particularly in arid regions (Figure 1.4). Solid fuel combustion in households is a major air pollution source in many low- and middle-income countries as well as the Western Balkans, while road transport makes smaller contributions—in stark contrast to widespread public perception.

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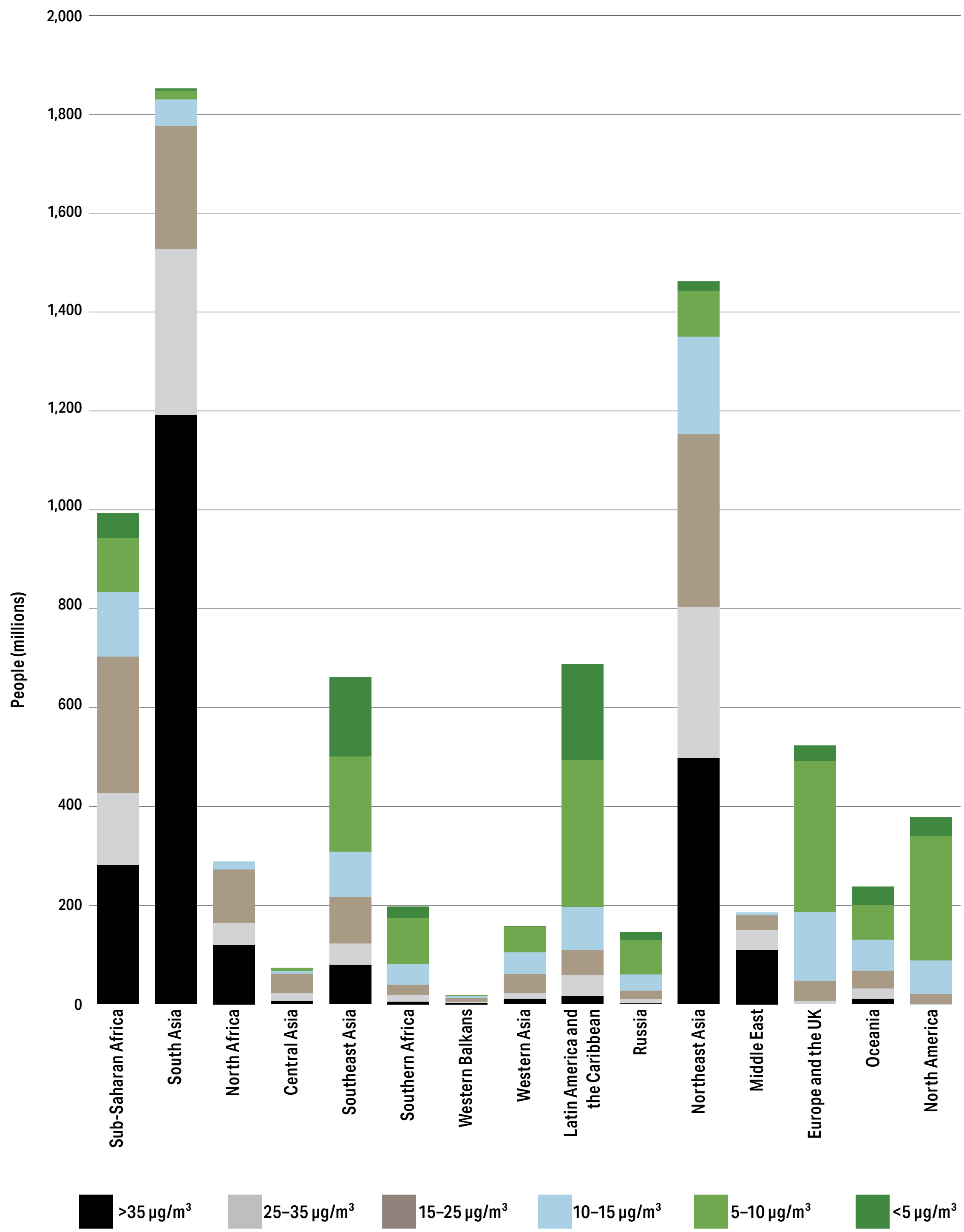
11 Note that the spatial resolution of the model calculations (11 by 11 kilometers) cannot detect small-scale local emission peaks.

12 While the study addresses management of pollution in ambient air, several emission sources cause additional health impacts through the exposure pathway in indoor environments. For instance, burning solid fuels for cooking and heating in households without proper ventilation adds to the high health burden from exposure to pollution from these sources in ambient air. The same sources responsible for primary and secondary $PM_{2.5}$ emissions also emit other pollutants, including greenhouse gases and short-lived climate pollutants with profound climatic and economic consequences. These sources are largely from fossil fuel combustion that also emits GHGs such as CO_2, nitrous oxide, and methane. Measures to reduce air pollution by $PM_{2.5}$ can simultaneously yield large climate mitigation and resilience benefits. GHG and SLCP emissions and measures to reduce them are therefore considered as part of this assessment.

Figure 1.3. Nearly 50 percent of the global population is exposed to $PM_{2.5}$ concentrations above 25 μg/m³

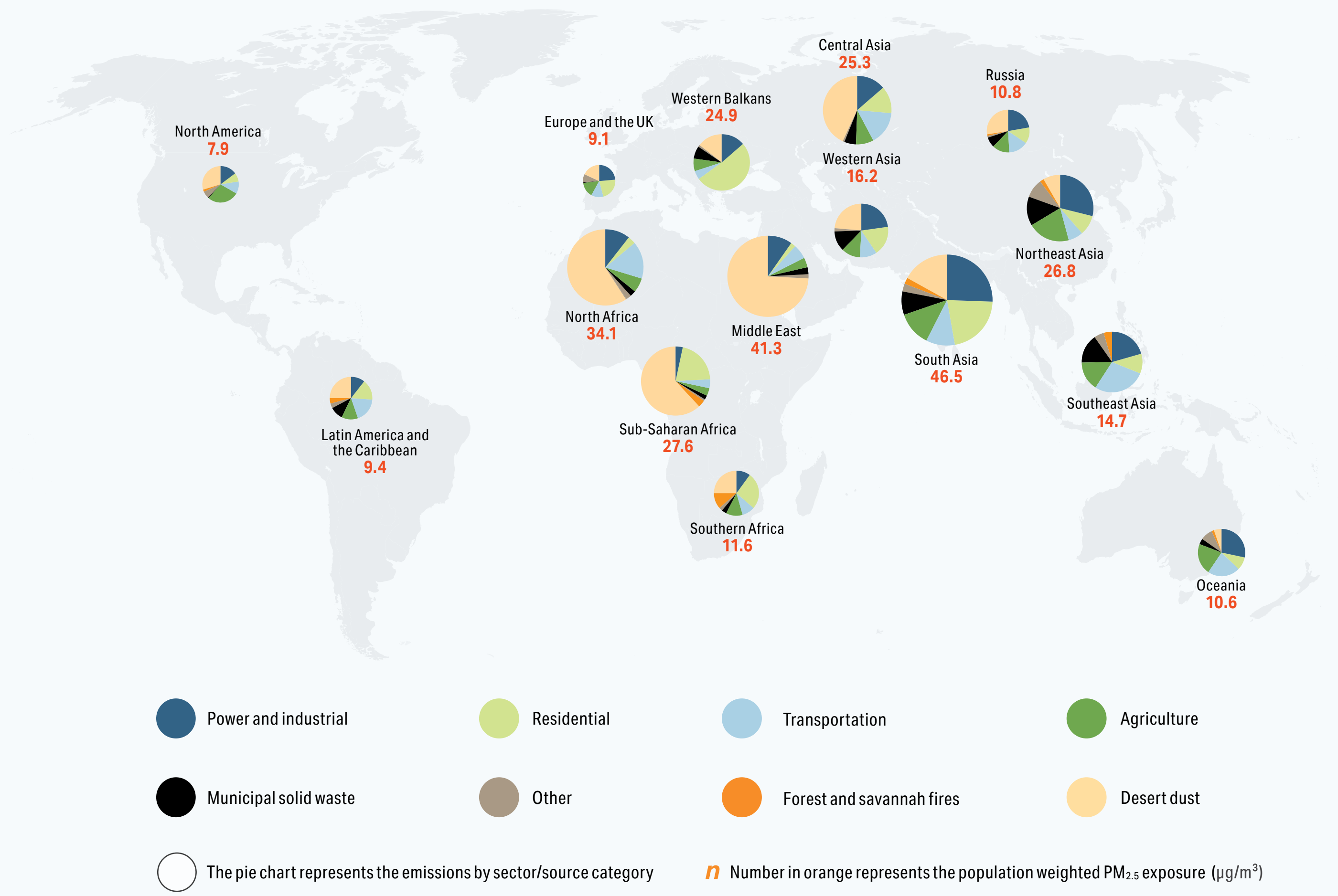
Number of people exposed to different $PM_{2.5}$ concentrations by world region in 2020 (including desert and soil dust)



Source: Original figure for this publication.

Figure 1.4. The main sources of pollution differ widely across regions

Key emission sources for population-weighted $PM_{2.5}$ exposure in 2020, by world region



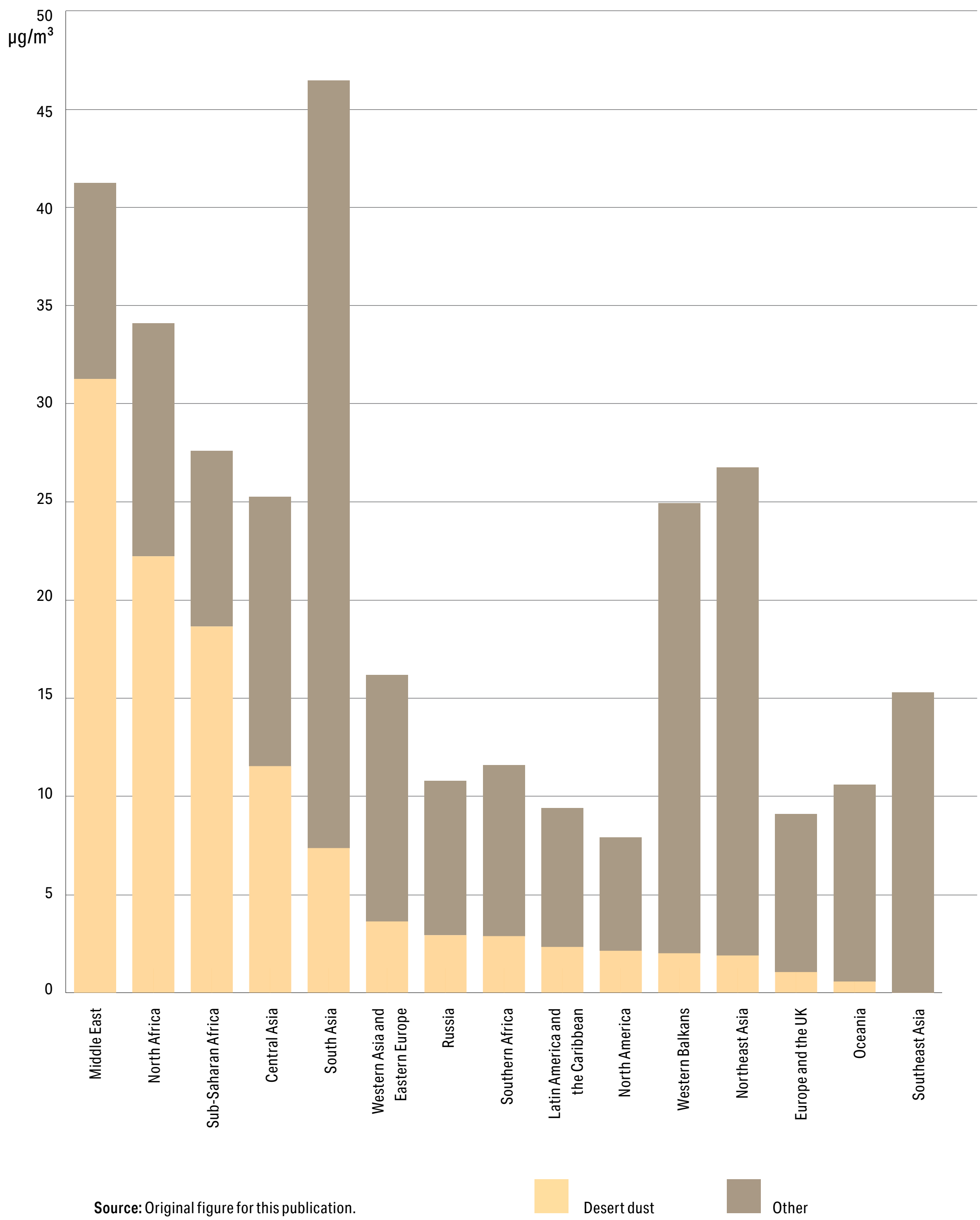
Source: Original figure for this publication.

Globally, anthropogenic emissions cause the majority of $PM_{2.5}$ exposure, although natural sources play a large role in desert regions, most notably the Middle East and Northern and Sub-Saharan Africa. Except for these regions, more than 50 percent of regional $PM_{2.5}$ exposure comes from anthropogenic emissions, with variations across regions.

In regions with the highest $PM_{2.5}$ concentrations, a substantial share of exposure emerges from desert and soil dust, especially in the Middle East (about 30 $\mu g/m^3$), and Northern Africa and Sub-Saharan Africa (about 20 $\mu g/m^3$). Eighteen percent of $PM_{2.5}$ exposure globally is caused by dust sources, with countries in the Middle East and Africa being particularly affected.

Figure 1.5. Dust is a significant contributor in regions with the highest $PM_{2.5}$ concentrations

Contribution of desert dust to $PM_{2.5}$ exposure in 2020, by region



Source: Original figure for this publication.

1.2 MODELING POLICY OPTIONS FOR REDUCING AIR POLLUTION

This report presents the findings of a scenario modeling exercise to determine which policy option would be most effective at reducing human exposure to air pollution by 2040.

Currently existing and proposed policies are expected to be insufficient to protect people from being exposed to hazardous $PM_{2.5}$ concentrations (above 35 μg/m³) in 2040.[13] A scenario modeling exercise conducted by the World Bank for this report found that implementing currently stated and proposed policies relating to air quality controls and decarbonization mitigations (the Stated Policies scenario described in Box 1.2) would cut global emissions of primary $PM_{2.5}$ by 6 percent by 2040. Despite this decline, these policies and measures may be insufficient to counter the effect of economic and population growth on exposure to $PM_{2.5}$. By 2040, the number of people exposed to $PM_{2.5}$ at concentrations of more than 35 μg/m³ (that is, exceeding WHO Interim Target 1) is expected to grow by 15 percent compared to 2020, while 21 percent more people are expected to be exposed to more than 25 μg/m³ (WHO Interim Target 2) (Figure 1.6). This is especially relevant for low- and middle-income countries, where ambient air pollution is expected to remain a critical concern because current policies offer limited prospects for improvement. Persistently high pollution levels will hamper these countries' development, impacting human health, economies, and overall quality of life.

By 2040, the distribution of $PM_{2.5}$ exposure is expected to become even more uneven. In Europe, the Western Balkans, North America, and China, stated policies are expected to outweigh increased pressure from economic growth, reducing $PM_{2.5}$ exposure compared to 2020. However, in all other regions—especially lower-income regions—stated policies are expected to be insufficient to compensate for pressures from economic growth. Without additional policy interventions, Sub-Saharan Africa, Northern Africa, Central Asia, Southeast Asia, and the Middle East are expected to face further growth in average exposure levels (Figure 1.7).

Higher exposure in the worst-affected regions will be driven by growth in anthropogenic emissions. By 2040, stated policies may have stabilized $PM_{2.5}$ exposure in South Asia, Western Asia, Russia, and the Middle East, and may have led to a decline in Southern Africa, the Western Balkans, China, Europe, and North America. Population exposure is expected to remain highest in regions where desert dust is an important contributor (that is, around the large deserts of Africa and the Middle East). However, growth in anthropogenic contributions to $PM_{2.5}$—especially in Africa—is expected to exacerbate $PM_{2.5}$ exposure levels.

13 The analysis adopted 2040 as the target year for the Clean Air scenario, in order to capture the full impacts of potential new policies and measures—including climate policies.

Box 1.2
Modeling scenarios and World Health Organization Air Quality Guidelines used in this report

This report uses scenario modeling to examine the effectiveness of policies and measures adopted by governments after 2005 to counteract increasing human exposure to air pollution driven by socioeconomic development and population growth.

Ultimately, the modeling exercise aims to identify policies that would achieve the following World Health Organization (WHO) Clean Air Targets against a 2020 baseline:

- **In regions not affected by desert dust**: Halving the number of people that breathe air polluted by $PM_{2.5}$ from all sources in concentrations of more than 25 $\mu g/m^3$ (WHO Interim Target 2).

- **In regions affected by desert dust**: Since measures to reduce natural dust are not available in the short term, halving the number of people that breathe air polluted with $PM_{2.5}$ from anthropogenic sources at concentrations of more than the WHO guideline value of 5 µg/m³.

The report examines the following four policy scenarios:[i]

- **Stated Policies.** This scenario assumes that low-carbon policies (the "Stated Policies Scenario [STEP]", as outlined in the International Energy Agency's [IEA's] World Energy Outlook 2021) and air pollution regulations and measures agreed upon by 2020 and incorporated into the International Institute for Applied Systems Analysis' Greenhouse Gas-Air Pollution Interactions and Synergies (GAINS) model (2021)[ii] will be effectively implemented (see Appendix B, Tables B1 and B2, for examples of policies and measures considered). This scenario is the "business-as-usual" scenario in this report, serving as a comparison point against which the effectiveness of other scenarios can be measured. A comparison between the Stated Policies scenario and a scenario that excluded stated policies but still considered increases in economic activities concluded that the Stated Policies scenario would result in a 6 percent decline in primary $PM_{2.5}$ by 2040.

- **Integrated Policies.** This scenario assumes that decarbonization policies (the "Sustainable Development Scenario" as outlined in the IEA's World Energy Outlook 2021, in which the global average temperature increase is limited to well below 2°C) and additional air pollution measures are implemented in an effective, cost-efficient manner by 2040. This scenario was found to be the most efficient and cost-effective method for achieving the Clean Air Targets. Table B2 in Appendix B provides examples of policies and measures assumed in this scenario.

- **Additional Climate Policies Only.** This scenario assumes the implementation of decarbonization policy measures from the IEA's World Energy Outlook 2021 Sustainable Development Scenario. Examples of measures are included in Appendix B, Table B3, column A.

- **Additional Air Quality Measures Only.** This scenario pursues the 2040 Clean Air Targets solely through additional conventional air quality management options (for example, end-of-pipe emission controls). Examples of such measures are included in Appendix B, Table B3, column B.

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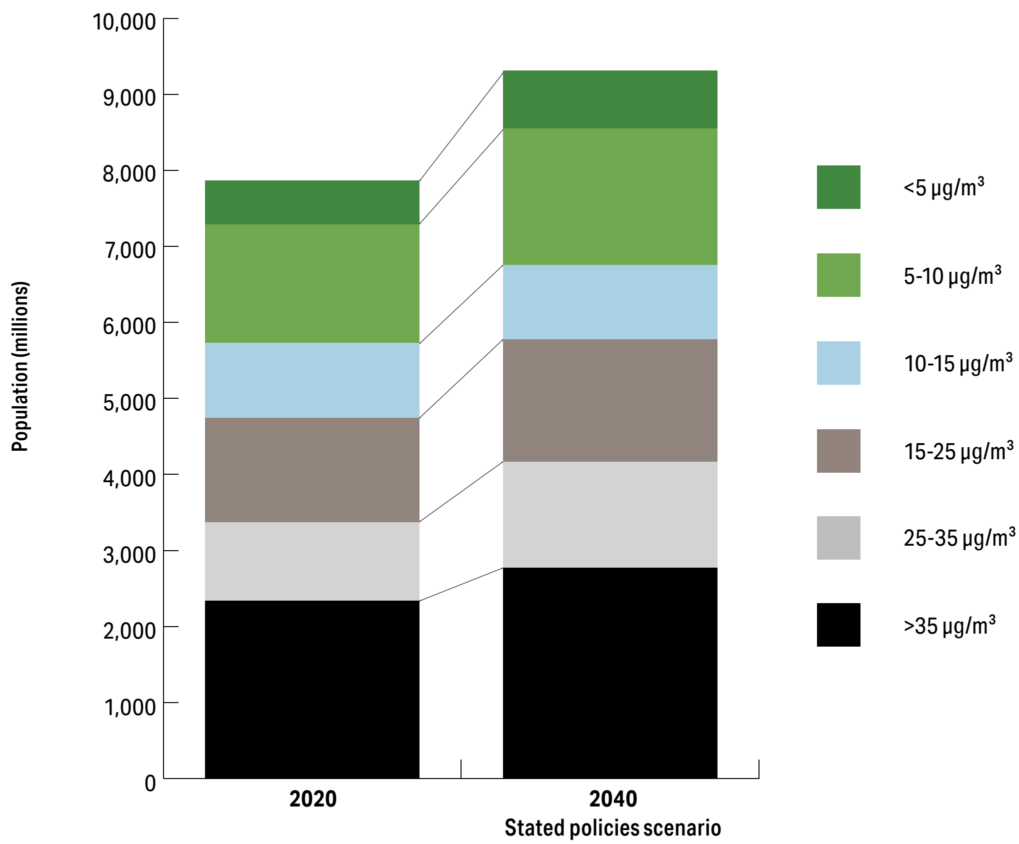
i See Appendix B for examples of measures considered in the analysis, including those considered in the Integrated Policies scenario.

ii The GAINS model explores cost-effective multipollutant emission control strategies that meet environmental objectives on air quality impacts (on human health and ecosystems) and greenhouse gases. Developed by the International Institute for Applied Systems Analysis, GAINS brings together data on economic development; the structure, control potential, and costs of emission sources; the formation and dispersion of pollutants in the atmosphere; and an assessment of environmental impacts of pollution. For more information, see: https://iiasa.ac.at/models-tools-data/gains

Figure 1.6. Under the current policy environment, even though the level of $PM_{2.5}$ pollution is expected to decrease, by 2040 the number of people exposed is likely to increase significantly

Global population exposed to different $PM_{2.5}$ concentrations (including from natural sources) in 2020 (actual) and in 2040 under the Stated Policies scenario (projected)



The categories in the figure mirror the World Health Organization's Interim Targets for $PM_{2.5}$. Dark blue = exceeding all targets. Light blue = Interim Target 1. Brown = Interim Target 2. Light green = Interim Target 3. Medium green = Interim Target 4. Dark green = WHO Air Quality Guideline.

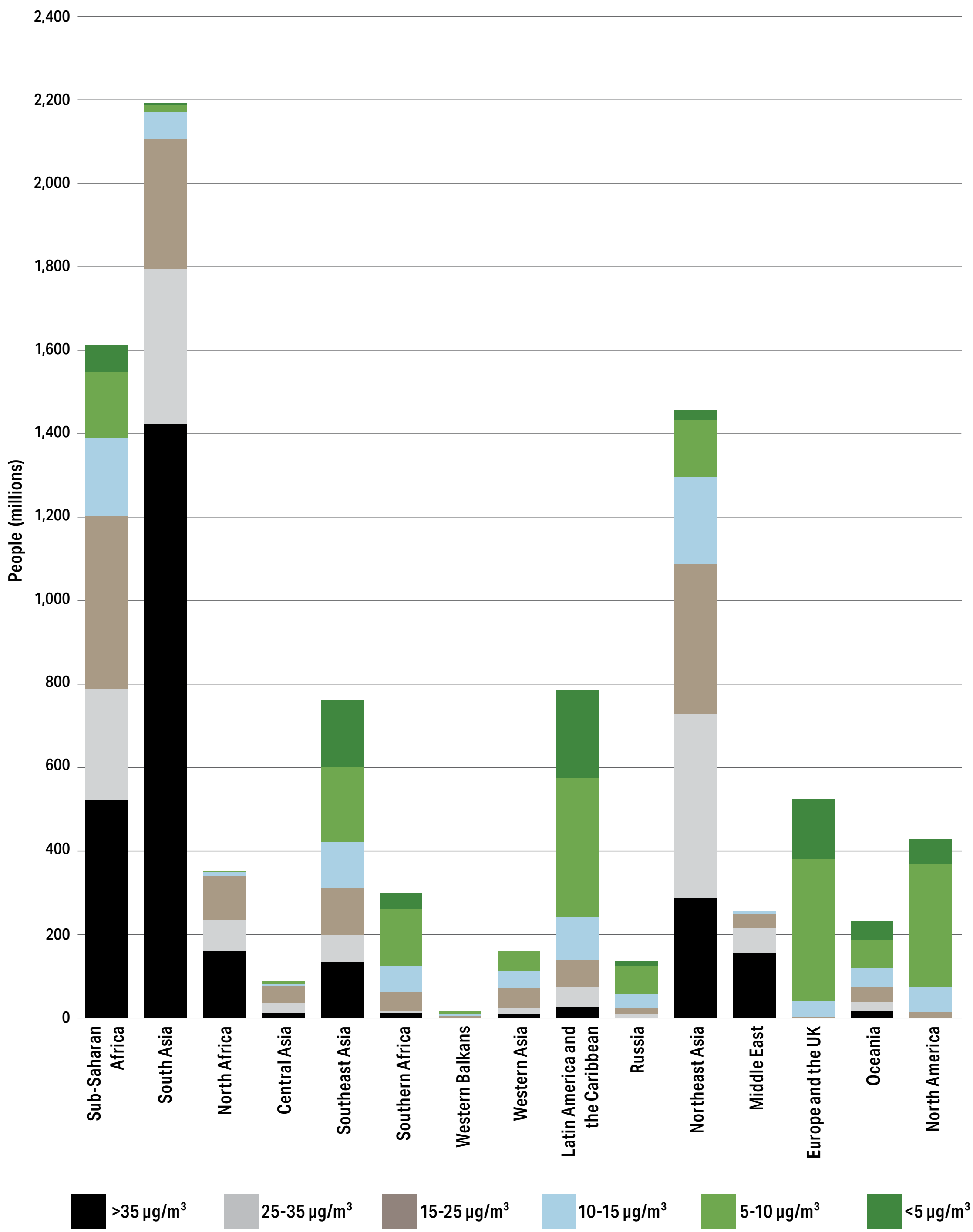
Source: Original figures for this publication.

Stated policies will be particularly effective in reducing $PM_{2.5}$ emissions from the use of solid fuel in households, especially in South Asia, Southern Africa, and the Western Balkans. However, solid fuel combustion for household heating and cooking will remain relevant in South Asia, Sub-Saharan Africa, and the Western Balkans. Industrial sources will be especially dominant in South Asia and China, while contributions from the transport sector are expected to be highest in Northern Africa, Southeast Asia, South Asia, and Central Asia. Municipal waste is expected to contribute substantially to $PM_{2.5}$ concentrations in South Asia, Southeast Asia, and China (Figure 1.8).

By 2040, global mortality attributed to air pollution would grow by between 8 and 10 percent under a Stated Policies scenario. That said, the practice of projecting mortality that is attributable to ambient air pollution is associated with significant uncertainties because the overall disease burden can be affected by several other factors, including existing public health challenges such as heart disease, diabetes, and other non-communicable diseases; socioeconomic factors such as poor access to health-care; lifestyle factors such as obesity and the availability of healthy foods; and aging populations.

Figure 1.7. Stated policies are likely to see lower income regions experience further growth in $PM_{2.5}$ exposure

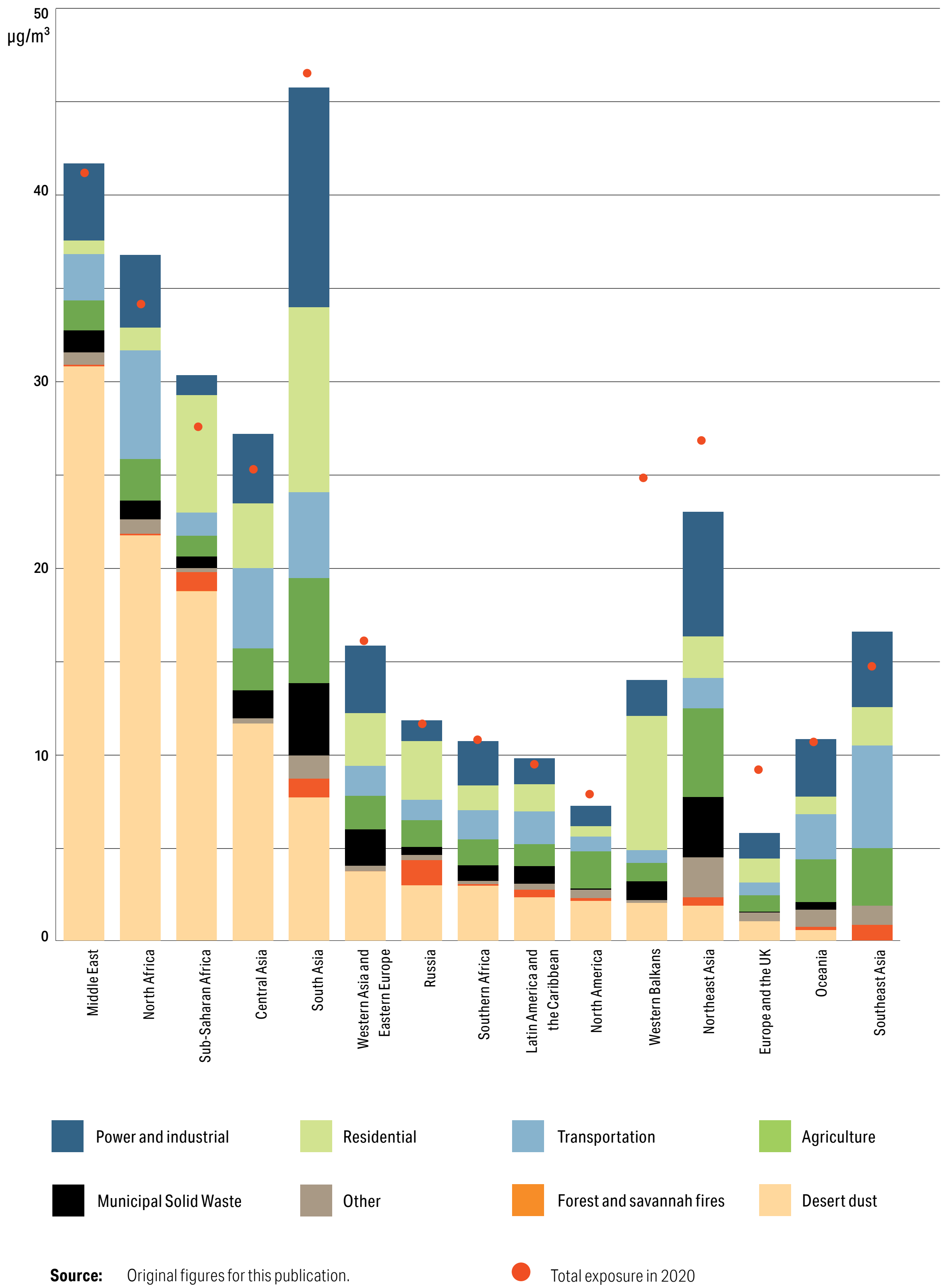
People exposed to varying levels of $PM_{2.5}$ concentrations (including desert and soil dust) across all regions in 2040 under the Stated Policy scenario



Source: Original figure for this publication.

Figure 1.8. The rise in anthropogenic emissions will drive the increase in air pollution exposure in the worst affected regions

$PM_{2.5}$ sources that contribute to population-weighted air pollution exposure under the Stated Policies scenario in 2040, compared with total $PM_{2.5}$ exposure in 2020



Source: Original figures for this publication.

1.3 THE CASE FOR INTEGRATED POLICIES

Substantial progress towards closing the $PM_{2.5}$ exposure gap by 2040 is possible through an integrated approach that combines conventional air quality management measures with energy and climate policies that are designed to achieve other goals, such as energy independence or reducing greenhouse gas emissions.

The analysis conducted for this report demonstrates that it is possible to achieve the Clean Air Targets, that is, to halve the number of people who will be exposed to $PM_{2.5}$ concentrations in excess of 25 μg/m^3 by 2040 against a 2020 baseline in most regions of the world. In desert regions, where $PM_{2.5}$ exposure is dominated by desert dust, the concentration has been lowered to 5 μg/m^3 and focuses only on $PM_{2.5}$ from anthropogenic sources.[14]

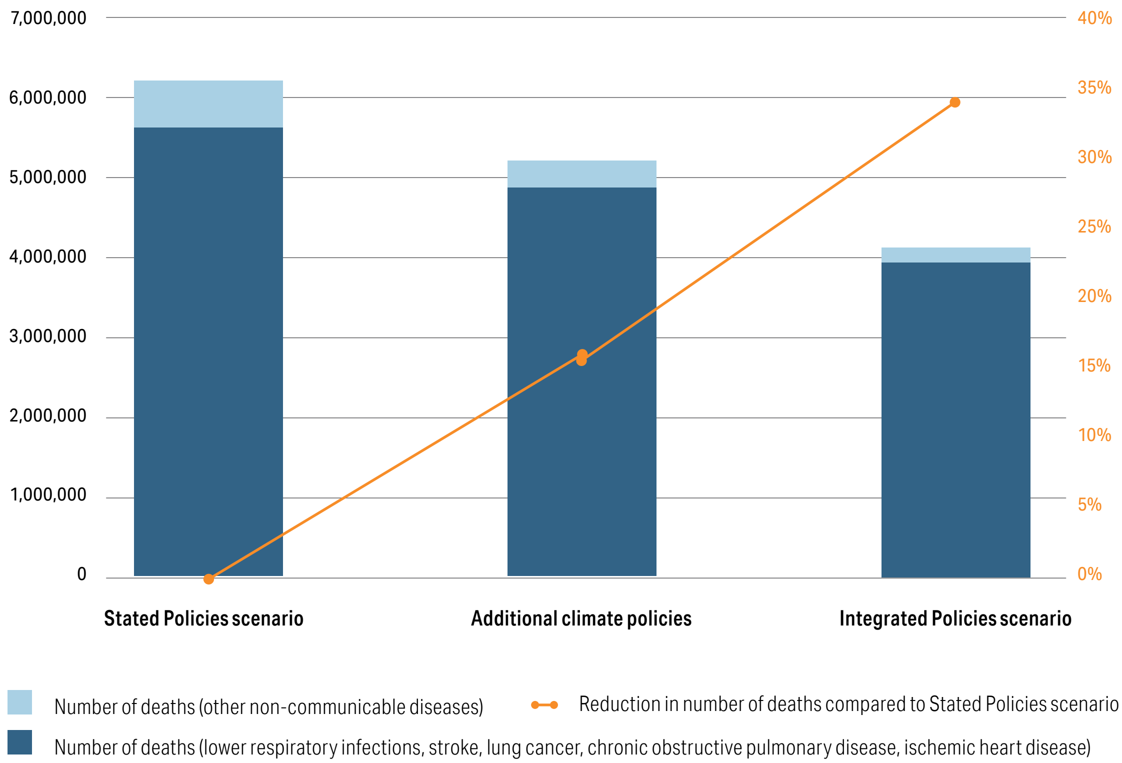
Implementing a suite of integrated policies would bring substantial health and economic benefits. Ambient air pollution-induced mortality is projected to increase from 5.7 million deaths per year in 2020 to 6.2 million deaths per year by 2040 under the Stated Policies scenario, partly driven by expected population growth in the most affected regions. However, using integrated policies could reduce these deaths to 4.1 million per year, representing a 35 percent reduction in mortality. The economic benefits of averted mortality are estimated to range between US$1.9 trillion and US$2.4 trillion (in 2021 terms) over the period, equal to between 1.6 and 2.1 percent of global GDP in 2040 (Figure 1.9).

Integrating AQM and climate/energy strategies into the suite of policies allows policy makers to capitalize on emerging developments and successes in these fields. Stated policies often do not include key measures that have been proven successful elsewhere, offering significant scope for additional air pollution abatement. Applying a comprehensive policy package that integrates stated policies with additional decarbonization and air pollution management and monitoring measures is expected to significantly reduce population-weighted exposure compared to 2020. The number of people exposed to $PM_{2.5}$ concentrations above 25 μg/m^3 (including desert dust) could fall from 3.4 billion people in 2020 to 2.2 billion people in 2040, amounting to a decrease from 46 percent to 24 percent of the total population exposed. In high-dust regions, implementing integrated policies could lead to an overall decline of less than 50 percent exposure to anthropogenic $PM_{2.5}$ concentrations of 5 μg/m^3.

14 Targets for desert sand-affected areas have been revised because this study did not model options for large-scale reductions in desert dust.

Figure 1.9. Integrated policies could cut attributable mortality by up to 35 percent against the Stated Policies scenario

Global ambient air pollution-attributable mortality in 2040 under different policy pathways



Source: Original calculations based on Burnett et al., 2018.

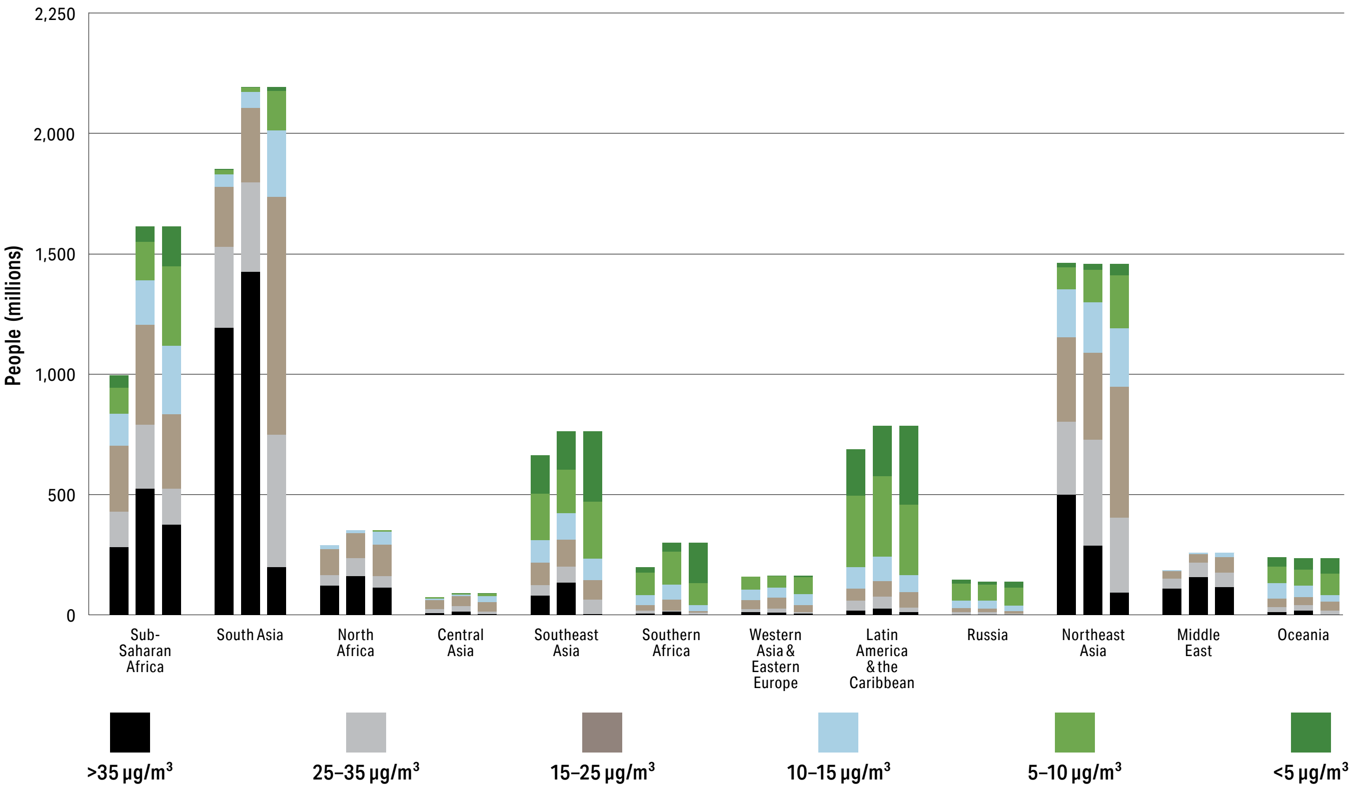
Improvements are expected to be greater for higher $PM_{2.5}$ exposure concentrations: the number of people exposed to more than 35 μg/m³ could decline from 2.3 billion in 2020 to 0.9 billion. These declines are expected to occur despite an overall anticipated increase in affected populations. Overall, implementing integrated policies would bring $PM_{2.5}$ exposure for 76 percent of the population in the 12 regions in line with the WHO Interim Target 2 (25 μg/m³) and for 90 percent with the WHO Interim Target 1 of 35 μg/m³ (including desert dust).

Most exposure reductions are expected to take place in lower-income regions. Due to more favorable baseline exposure conditions and broader, more effectively implemented stated policies, high-income regions are expected to experience a relatively modest gain from adopting integrated policies. On the other hand, about two-thirds of the people who are expected to attain WHO Interim Target 2 (25 μg/m³) through implementing integrated policies live in South Asia and about one-third lives in China. The remainder is largely concentrated in Sub-Saharan Africa (Figure 1.10).[15]

15 Reductions in population-weighted exposure are costly to achieve, making them especially challenging to achieve in low-income countries, where ambitious measures would consume a larger share of GDP. The potential for improvement also varies by region due to varying topographic and physical conditions; different levels of socioeconomic development, technology penetration, energy prices, and affordability; corporate sustainability

Figure 1.10. Low-income regions would benefit the most from implementing integrated climate/energy and air quality management policies

Number of people exposed to varying concentrations of $PM_{2.5}$ (including from natural sources) in 2020 (actual) and 2040 (projections based on Stated Policies and Integrated Policies scenarios)



Europe and the UK, the Western Balkans, and North America are excluded because the Stated Policies scenario would, by 2040, largely eliminate exposure to PM2.5 levels exceeding 25 μg/m³in these regions if all stated measures are implemented.

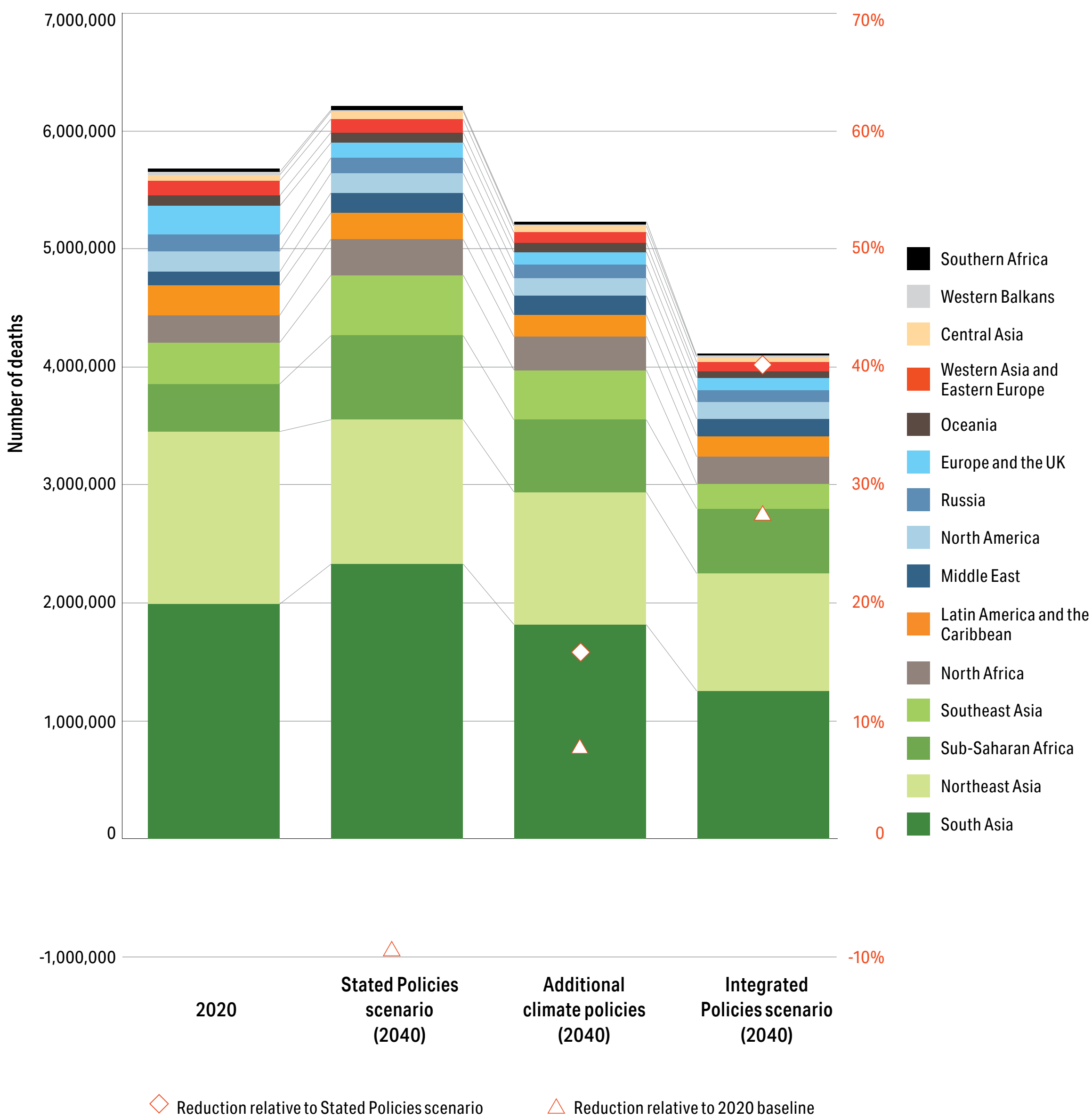
Source: Original figure for this publication.

While mortality attributed to air pollution is expected to decline across all world regions, low-income regions are anticipated to benefit the most from implementing integrated policies. Although integrated policies are expected to deliver benefits across all geographies, 66 percent of the reduction in ambient air pollution-attributable mortalities are expected to be focused on Southeast Asia, South Asia, and Southern Africa.

commitments; social and behavioral factors; and institutional factors, including the ambition of current air quality management policies. Because of these factors, some of the lower-income regions (and the largest numbers of people affected by high exposure) face lower reduction potentials.

Figure 1.11. The Integrated Policies scenario could cut attributable mortality by about 35 percent against the Stated Polices scenario

Reduction in ambient air pollution-attributable mortality by 2040 in an Integrated Policies and with the implementation of additional climate policies, by region



Source: Original calculations based on Burnett et al., 2018.

Box 1.3.
Case study: A "35-by-35" aspirational goal for South Asia

The Indo-Gangetic Plain and Himalayan Foothills (IGP-HF)—a 700,000 square kilometer area that includes parts of Bangladesh, Bhutan, India, Nepal, and Pakistan—is home to about 11 percent of the world's population (875 million people), two-thirds of whom live in rural yet often densely populated settings. The remaining third of the population lives in dense urban centers.

The IGP-HF suffers from the worst air pollution on the planet, with an annual average population-weighted exposure of 62 $\mu g/m^3$ between 2020 and 2024 across the entire area, peaking in urban centers like Lahore, Dhaka, Multan, Delhi, and Kolkata, which experience annual average concentrations of between 100 $\mu g/m^3$ and 150 $\mu g/m^3$. The human and economic toll of this is enormous: ambient air pollution caused more than 1.1 million premature mortalities in 2020 and incurred welfare costs equivalent to more than 11 percent of local GDP in IGP-HF jurisdictions.* The knock-on human and economic impacts due to cognitive decline and reduced urban economic competitiveness will be felt for decades.

While air pollution poses a chronic health threat in the IGP-HF area throughout the year, national and subnational governments have prioritized addressing localized seasonal peaks in air pollution that occur due to periodic events such as forest fires, the construction of bricks, and burning of crop residues. Ambient $PM_{2.5}$ concentrations during such episodes range widely, with 24-hour averages of up to 500 $\mu g/m^3$ observed during acute episodes. Annual average concentrations of between 100 and 150 $\mu g/m^3$ have been measured in IGP-HF urban centers.

ADOPTING A TRANSBOUNDARY AIRSHED APPROACH

With the support of the World Bank and the International Center for Integrated Mountain Development, regional partners have jointly agreed to take a coordinated approach to air pollution by adopting common methods for monitoring air quality and setting an ambitious goal of limiting pollution to below WHO Interim Target 1 (35 $\mu g/m^3$), averaged across the IGP-HF region, by 2035—also known as the "35-by-35" goal (Figure 1.12).

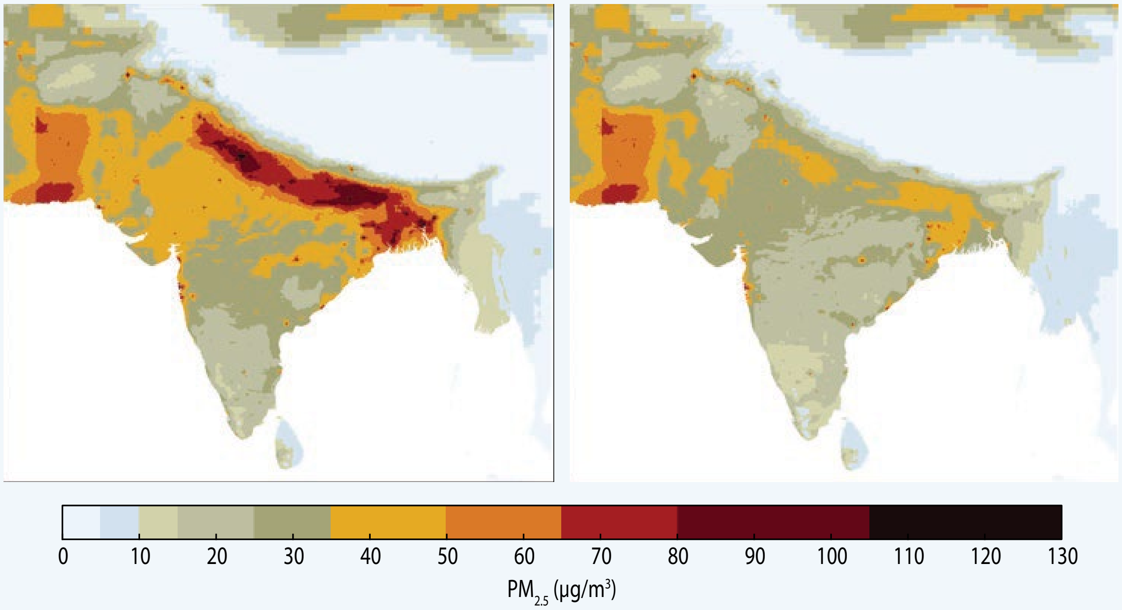
Achieving the "35-by-35" goal will require concerted effort by all 12 jurisdictions** within the region, as well as significant support from development partners, including the World Bank. If successful, more than 462,000 lives will be saved each year—a reduction of more than 41 percent against current premature mortality levels due to $PM_{2.5}$ concentrations.

Working together to adopt integrated policies that blend air quality measures with decarbonization policies would enable the regional partners to achieve their "35-by-35" goal far more quickly, and at a 30 percent lower cost (by avoiding regret investments and generating co-benefits) than if they tried to achieve the same results through individual and uncoordinated action (World Bank, 2022a, 2023a, and 2025).

Meeting the "35-by-35" goal for the IGP-HF region—the most air-polluted part of South Asia—is a critical point on the trajectory towards achieving the 25 µg/m³ goal at national levels by 2040 for countries in the region. Hence, achieving the "35-by-35" objective for the IGP-HF region is in sync with reaching the national and global targets outlined in this report by 2040.***

The trajectory needed is not without precedent. The "35-by-35" target will require an annual average reduction in population-weighted exposure of about 5 percent across the area. This is consistent with a pathway that would halve global exposure to $PM_{2.5}$ concentrations of 25 µg/m³ by 2040, as described in this section. While ambitious, this trajectory is possible. Countries such as China have already demonstrated rapid successes, reducing $PM_{2.5}$ concentrations in the North China Plain by about 65 percent between 2013 and 2024/25—an annual average reduction in $PM_{2.5}$ concentrations of 8.4 percent. Experience has shown that when governments make serious and sustained efforts to embrace the princiles of effective air quality management, cleaner air follows (see Box 4.1 for examples).

Figure 1.12. Aspirational "35 by 35" target for the Indo-Gangetic Plain and Himalayan Foothills



The left panel shows 2018 population-weighted annual average exposure to $PM_{2.5}$, which exceeded WHO Interim Target 1 by a factor of 20 or more across large parts of the IGP-HF region.

The right panel illustrates improved air quality through regional coordination and the application of common abatement measures to limit $PM_{2.5}$ concentrations to 35 µg/m³ by 2035 (the "35-by-35" target). This is expected to save more than 462,000 lives each year while reducing costs by of abatement significantly.

Source: World Bank, 2023a.

* This number excludes deaths due to COVID-19. See Appendix D for details.

** The 12 jurisdictions include: Nepal, Bangladesh, and Bhutan; as well as Uttar Pradesh, Haryana, Punjab, Bihar, West Bengal, and Jharkhand states; the Delhi and Chandigarh municipalities in India; and Punjab province in Pakistan.

*** An overview of key World Bank recommendations for achieving the "35-by-35" goal in IGP-HF is outlined in Box ES2.

1.4 DEVELOPMENT CO-BENEFITS

Integrated policies to reduce air pollution are expected to deliver significant development co-benefits and climate mitigation gains

Addressing outdoor air pollution has significant development co-benefits to health, economy and development. Ambient (outdoor) air pollution kills roughly 5.7 million people globally every year. Exposure to $PM_{2.5}$ causes cardiovascular and respiratory diseases, leading to conditions such as such as ischemic heart disease, stroke, lung cancer, chronic obstructive pulmonary disease, and Type 2 diabetes mellitus.[16] It also has cognitive impacts in children that can span generation: each 1 micro-gram per cubic meter increase in $PM_{2.5}$ concentration is linked to a decrease of 0.27 points in full-scale IQ, an increase of 0.39 points in performance IQ, and a decrease of 0.24 points in verbal IQ.[17] The economic cost of outdoor air pollution is estimated at nearly 5 percent of global GDP, from the costs of poor health and early deaths, and also from productivity loss and cognitive impacts that can span generations.

The package of integrated policies would result in improvements in health outcomes through reduced mortality and associated economic benefits. The package of integrated policies would result in decline in number of people exposed to levels exceeding 35 $\mu g/m^3$ from 2.3 billion in 2020 to 0.9 billion in 2040, and those exposed to levels exceeding 25 $\mu g/m^3$ would decrease from 3.4 billion people in 2020 to 2.2 billion in 2040. This would reduce the number of deaths attributed to outdoor air pollution to 4.1 million per year in 2040, with the estimated economic benefits of averted mortality between $1.9 trillion and $2.4 trillion (in 2021 terms) over the period, equivalent to between 0.8 percent and 2.1 percent of global GDP in 2040. Reducing outdoor air pollution can have positive impact in terms of productivity: a 20 percent decrease in $PM_{2.5}$, is associated with a 16 percent increase in employment growth rate and a 33 percent increase in labor productivity.[18]

16 Sustainable Development Goal Indicator 3.9.1: Mortality attributed to air pollution. Geneva: World Health Organization; 2024. Licence: CC BY-NC-SA 3.0 IGO.

17 Alter NC, Whitman EM, Bellinger DC, Landrigan PJ. Quantifying the association between $PM_{2.5}$ air pollution and IQ loss in children: a systematic review and meta-analysis. Environ Health. 2024 Nov 18;23(1):101. doi: 10.1186/s12940-024-01122-x. PMID: 39551729; PMCID: PMC11572473.

18 Soppelsa, Maria E.; Lozano-Gracia, Nancy; Xu, L. Colin. 2019. The Effects of Pollution and Business Environment on Firm Productivity in Africa. Policy Research Working Paper;No. 8834. © World Bank, Washington, DC. http://hdl.handle.net/10986/31599 License: CC BY 3.0 IGO.

Policies and measures that reduce air pollution in various sectors provide co-benefits to human health and productivity. For example, addressing residential heating and cooking would reduce outdoor air pollution, but will also reduce the burden of mortality and morbidity associated with indoor household air pollution due to burning of biomass for cooking and heating reducing associated mortality, morbidity and economic damages associated with household indoor air pollution. In 2021, over 500 thousand deaths of children under five years of age were attributed to household particulate matter exposure. Furthermore, implementing household energy efficiency measures, such as improving insulation, upgrading to more efficient heating solutions that use renewable energy, and using natural gas as a transition fuel, can significantly reduce energy demand and contribute to energy and financial savings.

Policies and measures that reduce air pollution emissions in different sectors provide co-benefits for sustainable economic growth and development. An increase of 1 percent in $PM_{2.5}$ concentration can lead to a decline in agricultural total factor productivity (TFP) by 0.104 percent, resulting in estimated global economic losses of approximately $5 billion per year. Mitigating air pollution can prevent these losses and improve crop yields and quality. This improvement can have beneficial effects on farmers' profitability, alleviate economic difficulties, and help prevent potential food shortages, particularly in areas heavily dependent on agriculture. Adopting measures that reduce air pollution can support more sustainable and resilient agricultural practices also reducing the overuse of fertilizer, saving production costs to farmers and to consumers, and improving soil health.

Similarly, measures and actions that reduce air pollution from open burning of waste, can contribute to achieving higher tiers of waste management with efficient waste collection, safe disposal, waste segregation at source, and increased recycling and material efficiency strategies. Land-use policies that prevent urban sprawl and promote dense, compact, and mixed-use urban form help to reduce air pollution emissions by minimizing travel distances, but they also enhance the effectiveness of modal shift strategies, thereby boosting their potential to reduce emissions. For example, cyclists in Copenhagen take 1.1 million fewer sick days collectively compared to non-cyclists and reap health benefits valued at $1.16 for every kilometer cycled instead of by car.

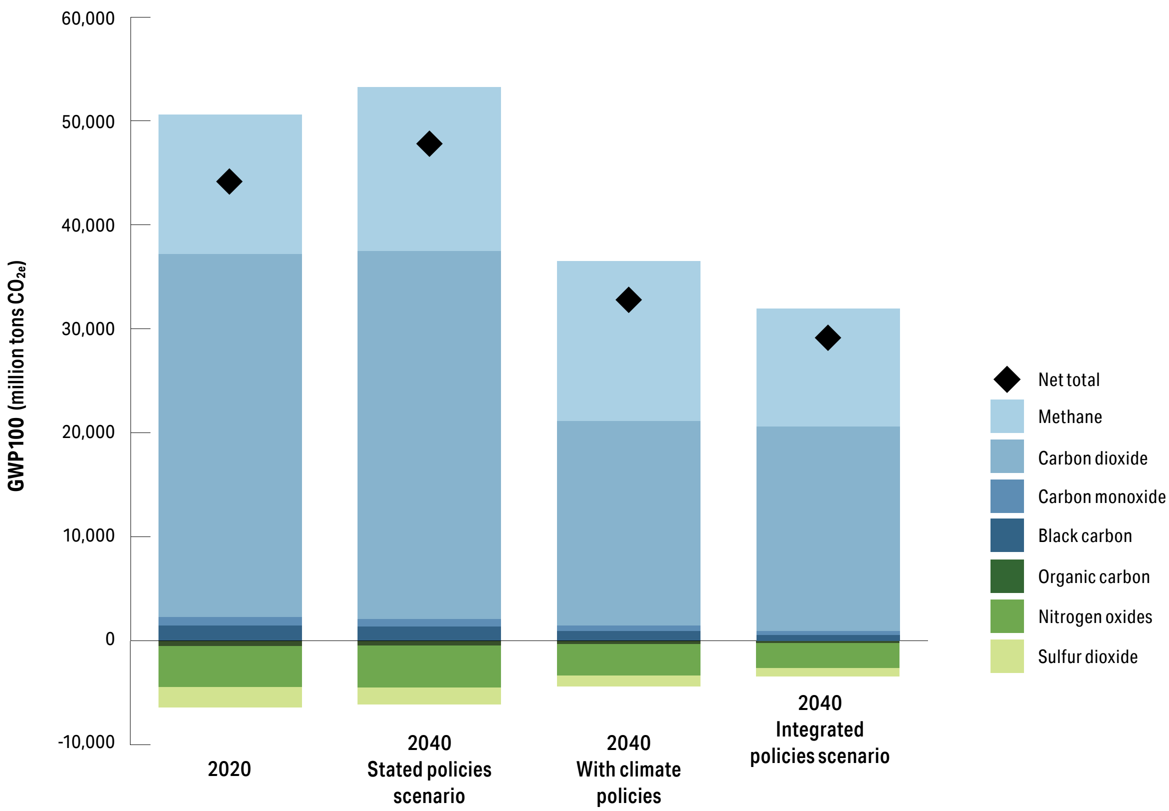
An integrated policy package that combines conventional air pollution control measures with decarbonization policies is expected to reduce warming black carbon emissions. Some $PM_{2.5}$ substances affect global temperature change in the near and mid term. Short-lived climate pollutants such as black carbon enhance radiative forcing and drive up temperatures while they are present in the atmosphere, which could range from a week to a few months. Lowering emissions of these substances would reduce this warming effect.

Implementing integrated policies at the global scale are expected to reduce black carbon emissions by almost two-thirds and carbon monoxide emissions by more than half relative to 2020. About 60 percent of these declines are expected to emerge as a co-benefit from decarbonization policies, mainly by eliminating solid fuels in households. The remaining 40 percent is linked to additional clean air measures such as banning the burning of crop residues and efforts to reduce emissions from diesel engines.

Given the current abundance of household solid fuel use in lower-income countries, most of these black carbon reductions are expected to occur in Sub-Saharan and Southern Africa, South

Figure 1.13. Integrated policies deliver climate mitigation benefits while reducing $PM_{2.5}$ exposure

Effect of reducing greenhouse gases and short-lived climate pollutants (i) under the Stated Policies scenario, (ii) with additional climate policies, and (iii) under the Integrated Policies scenario on 100-year global warming potential by 2040, compared with actual data in 2020



Source: Original elaborations based on GWP100 climate metric.

Asia, China, and Mongolia. The benefits of this reduction may be counteracted by a parallel reduction in atmospheric cooling substances such as SO_2 and nitrogen oxides (by an estimated 60 percent and 40 percent, respectively), which are precursors to the production of secondary $PM_{2.5}$. Ultimately, additional air pollution controls are expected to bring about only small net climate benefits.

Air pollution controls can affect greenhouse gas (GHG) emissions and—through various pathways—temperature changes. Air pollution controls can lead to lower CO_2 emissions if they are effective in reducing the consumption of fuels with high CO_2 emissions.[19] Such controls include various energy-conservation measures, switching to electric vehicles, or transitioning to renewable energy. In this way, implementing an integrated suite of air quality and climate/energy policies is expected to result in 45 percent lower CO_2 emissions and 28 percent lower methane emissions compared to implementing already stated policies alone. The CO_2 reductions are linked to the energy/ climate

19 All measures that are expected to deliver CO_2 emissions abatement are included in the energy and climate policy package, so no further CO_2 reduction benefits are anticipated from additional measures.

policy measures, while the cuts in methane emissions stem from clean air measures such as improved municipal waste management and reducing the extraction and production of fossil fuels.

Changes in long- and short-lived pollutants will affect global temperature in the coming decades, with some pollutants expected to contribute to warming while other substances will unmask the ongoing warming impact of long-lived GHGs. Instead of focusing on the climate impacts of a single pollutant, it is crucial to consider the net climate impacts of all pollutants when assessing measures to reduce the burden of air pollution on public health.

Although the combined climate impacts of warming and cooling $PM_{2.5}$ precursor substances—especially compared with those of long-lived GHGs—are still being quantified through scientific research, the known benefits of clean air justify immediate action. Even though more is known about the climate impacts of individual substances, the combined effects of warming and cooling substances with similar atmospheric lifespans are still under investigation, with complex geophysical processes, different lifespans, and feedback loops in the global climate system introducing uncertainty into assessments

Implementing integrated policies will likely result in a 40 percent net reduction in overall global warming potential over 100 years (GWP100), compared with implementing already-stated policies only.[20] While 80 percent of this decline is expected to stem from decarbonization policy measures, it is worth noting that the remaining 20 percent are linked to additional clean air measures. Municipal waste management, for example, would also mitigate methane emissions, which are only rarely considered in conventional low-carbon policies. These methane reductions by far outweigh some net increases in GWP100 caused by needing to lower SO_2, nitrogen oxides, and organic carbon emissions to achieve the Clean Air Targets (Figure 1.13).

20 This report uses the climate metric of the Global Warming Potential over 100 years (GWP100). For long-lived greenhouse gases, it uses the GWP100 as outlined in the 6th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2022). For short-lived warming and cooling pollutants, it uses the GWP100 from Tanaka et al., 2019, which included a special focus on the conditions in developing countries in Asia and Africa.

Box 1.4. $PM_{2.5}$ and greenhouse gas emissions: Common issues and sources

Navigating the interplay between air quality management and climate change mitigation requires an understanding of their shared and unique challenges, the distinct management approaches, and interrelated considerations in both fields. The main considerations are discussed below.

Substances: Air pollutants and greenhouse gases (GHGs) each have their own distinct characteristics and main sources. The key GHG is widely understood to be carbon dioxide (CO_2) because of its long atmospheric lifetime and its anthropogenic origins. The key air pollutant is particulate matter with a diameter less than 2.5 micrometers (or $PM_{2.5}$) due to its adverse health impacts. Some substances, such as black carbon, are both air pollutants and GHGs. Black carbon is primarily produced by incomplete combustion. Other air pollutants that also cause climate warming include ground-level ozone, volatile organic compounds, and carbon monoxide.

Air pollutants as climate coolants: Some air pollutants act as climate coolants. Sulfate aerosols generated from SO_2 emissions have a cooling effect by reflecting sunlight and offsetting a portion of the warming caused by GHGs. Other air pollutants such as nitrogen dioxide and ammonium also have a climate cooling impact.

Emission sources: There is a considerable overlap in the sources that pollute the air and emit GHGs. Industrial activities, transportation, energy production, fuel combustion, and agricultural practices all emit both air pollutants and GHGs. On the other hand, there are activities (such as construction) that emit air pollutants but do not emit GHGs. Despite this overlap in sources, climate change mitigation (CCM) policies tend to prioritize large emission sources (such as power plants using fossil fuels), whereas air quality management (AQM) policies may prioritize smaller emission sources (such as solid fuel cooking and heating), which have large impacts on local air pollution concentrations.

Emissions versus concentration: CCM primarily focuses on reducing emissions of GHGs like CO_2, methane, and nitrous oxide. AQM focuses on reducing pollutant concentrations. In the case of CO_2, the link between the concentration of carbon in fuels and CO_2 emissions is proportional. However, the relationship between $PM_{2.5}$ emissions and concentrations is more complex.* Similarly, tradeoffs between CO_2 emissions and particulate concentrations are not straightforward.

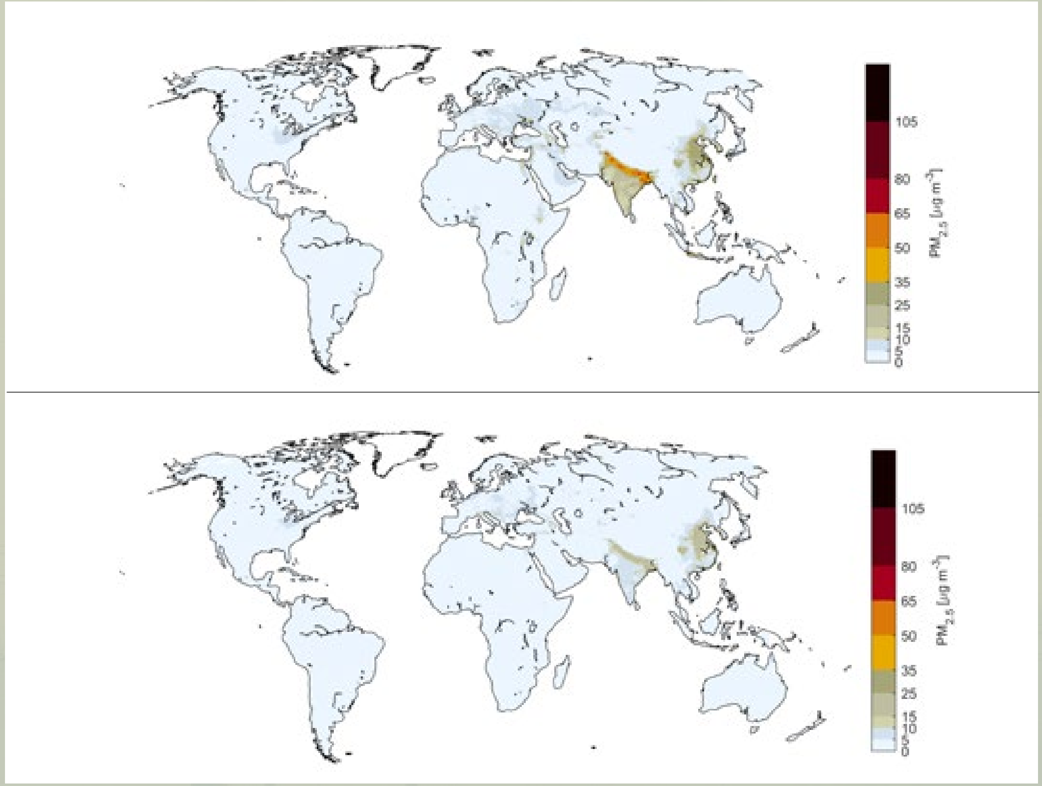
Dispersion characteristics: Understanding the dispersion characteristics of pollutants is crucial for effective AQM and reducing related health impacts. For instance, a large emissions source such as a power plant might not contribute much to urban air pollution due to the dispersion characteristics of emissions that are ejected at a high velocity from a tall stack with a wide diameter. By contrast, a smaller emission source (such as a residential cook stove) could have a major impact on urban air pollution because emissions are released close to where people live, at a lower height, and at lower velocities and temperatures. Dispersion characteristics do not play a major role in CCM.

Location of emission sources: Where air pollution sources are located is pivotal in AQM. Local air quality can be significantly influenced by the location of sources and the effect this has on local meteorological and topographic conditions; the size of populations and whether they are upwind or downwind; and airshed characteristics. Spatial factors therefore play an important role in AQM strategies. The location of a GHG emission source is unimportant from a climate perspective because GHG emissions act on a global scale.

Management domain: The institutions primarily responsible for AQM and CCM differ. While AQM is mainly managed at local level, CCM is usually managed at the national and global level. However, AQM at the national and transboundary levels are crucial for effectively addressing regional air quality challenges.

Achieving AQM and CCM policy objectives: Reductions of GHG emissions in line with existing objectives, namely the Nationally Determined Contributions (NDCs) under the Paris Agreement, were found to result in air pollution levels that did not meet health-driven air quality targets in several regions in the world (Amann et al., 2020). It is clear that decarbonization policies on their own will not reduce air pollution to safer levels. Measures that target air pollution from various sources are also needed to meet air quality standards around the world (Figure 1.14).

Figure 1.14. Modeled $PM_{2.5}$ concentrations from anthropogenic sources in 2040 in the Stated Policies scenario (top) and the Integrated Policies scenario (bottom)



The Stated Policies scenario illustrates the effect of climate-related policies that were in place by 2018, including the NDCs. The Integrated Policies scenario adds to these policies additional measures relating to air pollution control, energy, agriculture, and food systems.

Source: Original figure for this publication.

* This relationship is defined by the impact of emission sources' dispersion characteristics on $PM_{2.5}$ concentrations, along with the secondary particulates formation through photochemical reactions in the atmosphere with SO_2 and nitrogen oxides.

2
MULTISECTORAL SOLUTIONS TO ACCELERATE ACCESS TO CLEAN AIR

Integrated policies are an appealing option for halving number of people exposed to annual average air pollution concentrations in excess of 25 μg/m^3.

While residential cooking and heating will be important sectors to target in many regions, solutions should ideally be multisectoral—targeting industry, waste management, agriculture, and transport—in order to be as effective as possible.

This section discusses the importance of taking an integrated (yet context-sensitive) approach to developing policies before delving into findings and recommendations for various sectors. It then suggests adaptive strategies to reduce the impacts of air pollution and discusses how air quality measures and climate change mitigation actions interact.

MAIN MESSAGES IN THIS SECTION

- Integrated policies should be context-specific and target a range of sectors to achieve the desired outcomes.
- The residential cooking and heating sector is responsible for a third of anthropogenic $PM_{2.5}$ emissions globally and presents an opportunity for achieving the Clean Air Targets, as defined in this report (see Box 1.2).
- Agriculture, industry, transportation, and solid waste also contribute significantly to air pollution, underscoring the need to treat air pollution as a multisectoral problem that requires multisectoral solutions.
- Air quality management and climate change mitigation policies may work synergistically but require careful consideration to minimize tradeoffs and maximize positive effects.

2.1 PRIORITIZING AN INTEGRATED APPROACH

Cutting exposure to air pollution through integrated policies is cost effective, but policies need to be sensitive to the local context.

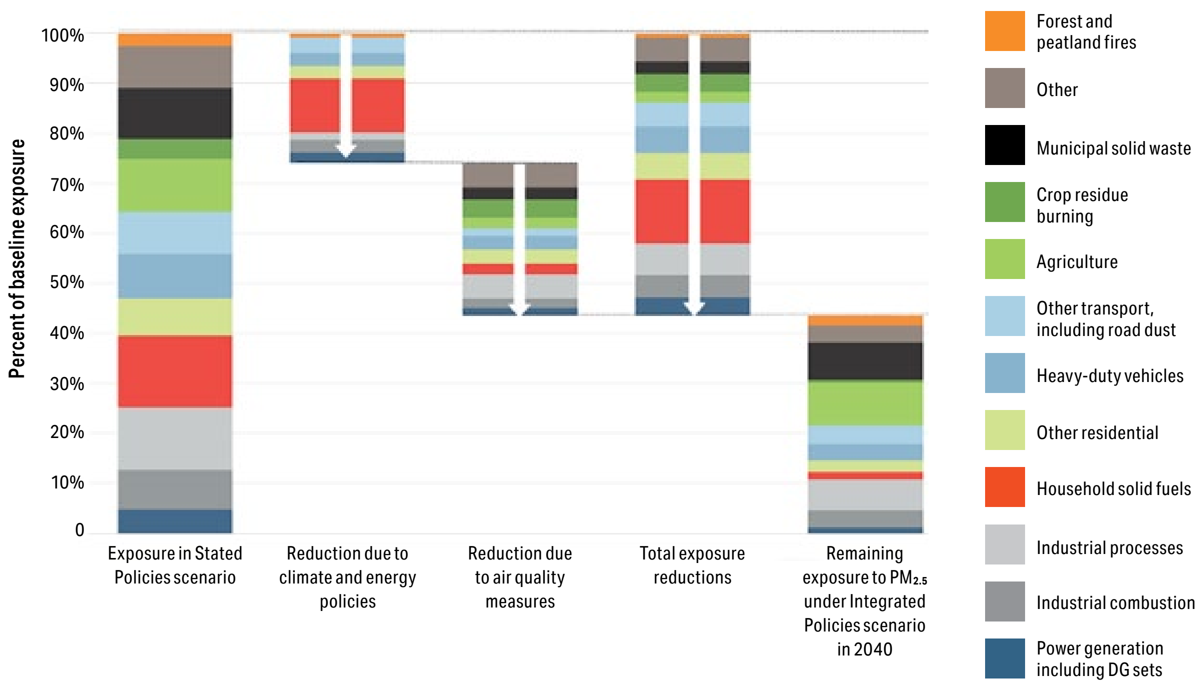
Scenario modeling conducted by the World Bank shows that integrated policies could achieve the Clean Air Targets (as defined in Box 1.2) at a 33 percent lower cost compared to a conventional AQM approach. However, to optimize the effectiveness of this approach, policy measures need to be sequenced based on carefully identified priorities.

Globally, about 45 percent of additional reductions in exposure to air pollution—that is, reductions over and above those secured by already-stated policies—is expected to be realized through decarbonization policies, most notably policies that aim to (i) secure universal, reliable access to clean fuels for heating and cooking and (ii) decarbonize the energy and industrial sectors. The remaining 55 percent is expected to be achieved through AQM measures across all sectors, with industrial processes, oil and gas production, transport, agriculture, and municipal waste management being key contributors (Figure 2.1). Implementing bans on burning agricultural residue will be a key driver for reducing air pollution in Southern Africa, China and Mongolia, Sub-Saharan Africa, and South Asia. End-of-pipe emission controls for road transportation will be critical in Northern and Southern Africa, Southeast Asia, and Northeast Asia (Figure 2.2). While such policies will curb anthropogenic emissions, they will not limit exposure to natural dust, which by 2040 is expected to remain the main source of air pollution in Africa and the Middle East. These regions will therefore need to pursue the largest reductions in air pollution from anthropogenic sources to achieve the Clean Air Targets.

The residential sector is expected to generate more than half of the exposure reductions needed to achieve the Clean Air Targets defined in Box 1.2. Different geophysical and economic conditions are expected to affect which sectors will be targeted by integrated policies and measures in different regions. That said, cost efficiency considerations indicate that about 55 percent of exposure reduction required to achieve the Clean Air Targets will probably come from the residential cooking and heating sector (Figure 2.3). In Sub-Saharan and Southern Africa, more than 50 percent of total exposure reductions are expected to come from measures to address the use of solid fuels (including biomass) in households for cooking. In Asia's low- and medium-income regions (that is, South, Western, and Central Asia) and in Latin America, the residential sector could account for about 30 percent of total reductions, with priority given to interior space heating with solid fuels.

Figure 2.1. Reducing air pollution exposure will require policy instruments tailored to the specificities of sectors and regions

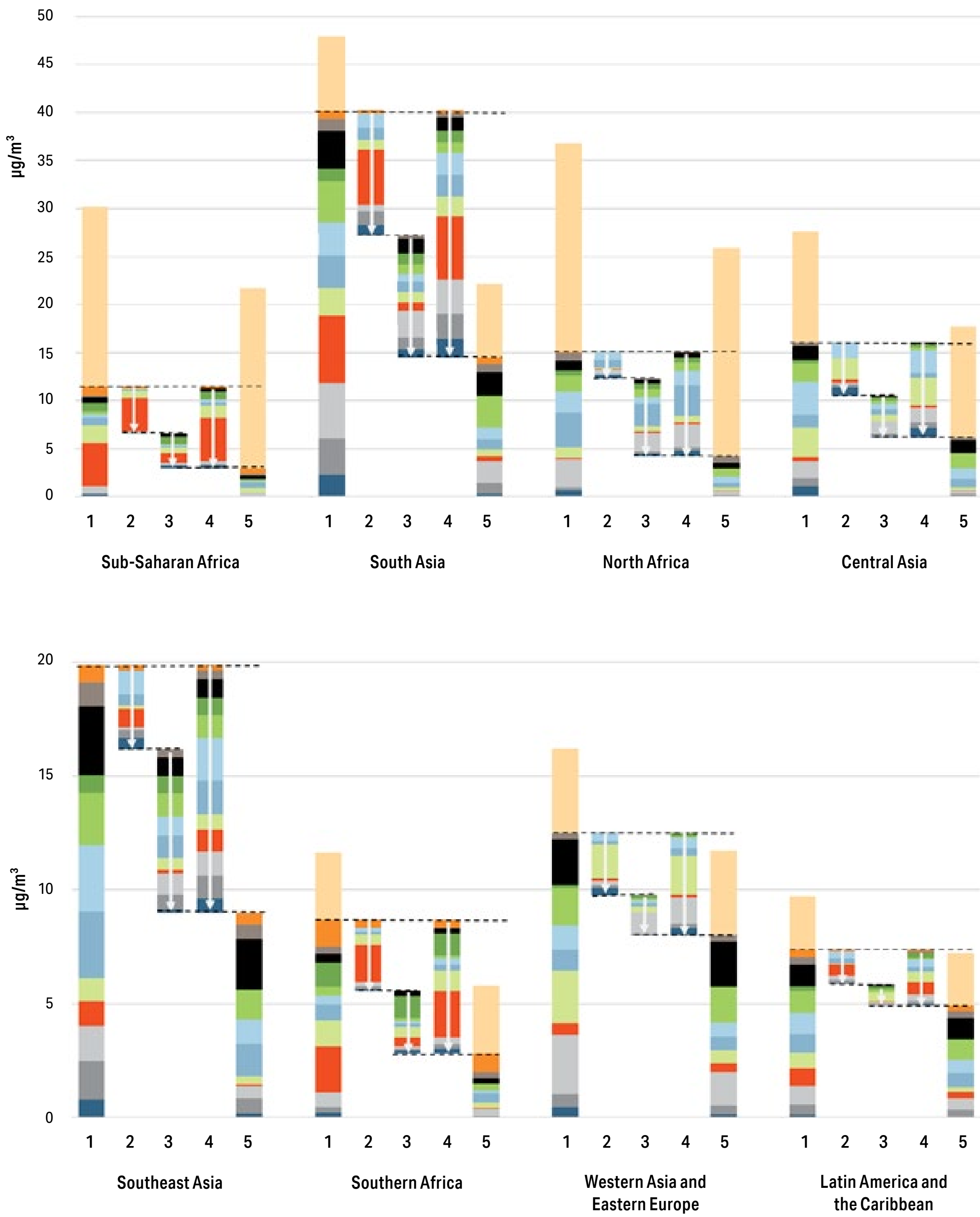
Comparison of anthropogenic $PM_{2.5}$ exposure between Stated Policies scenario and Integrated Policies scenario in 2040, by sector

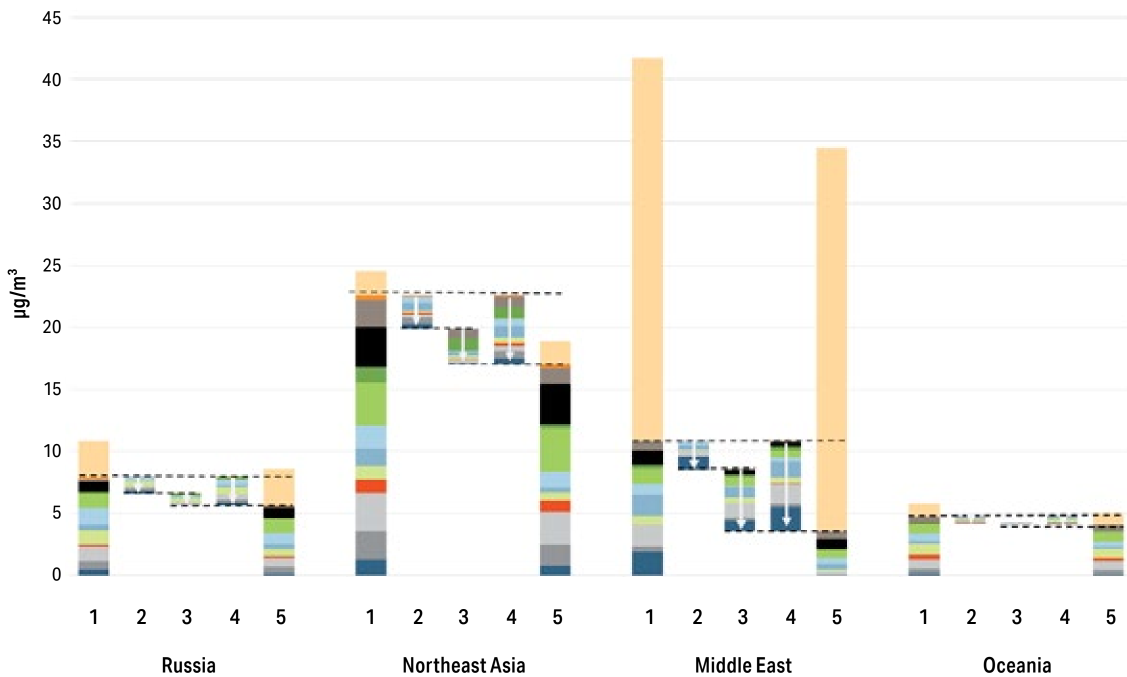


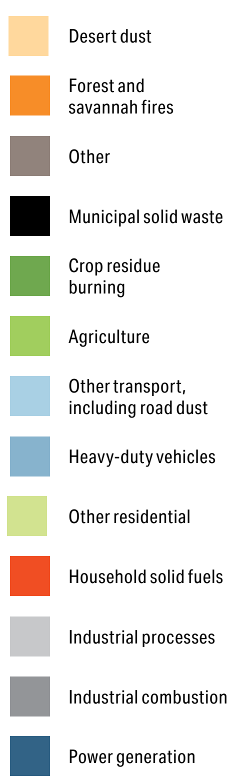
Source: Original figure for this publication.

Achieving the Clean Air Targets (as defined in Box 1.2) in a cost-effective manner will require interventions across all sectors. The goal would be unattainable if policies and measures are implemented only in one sector. In most regions, further control of industrial emissions is expected to account for a quarter of total exposure reductions, reaching closer to 50 percent in West Asia and Eastern Europe, Russia, and the Middle East. Vehicle emission controls are expected to account for 40 percent of total reductions in Northern Africa, but only 20 percent or less in South Asia, Sub-Saharan and Southern Africa, Latin America, and other regions (Figure 2.3). The sections that follow present the key innovative solutions and latest measures that can have an impact on accelerating access to clean air.

Figure 2.2. Comparison of annual $PM_{2.5}$ exposure between Stated Policies scenario and Integrated Policies scenario in 2040, by sector and regions







1 = Exposure under the Stated Policies scenario

2 = Reduction in exposure due to climate and energy policies

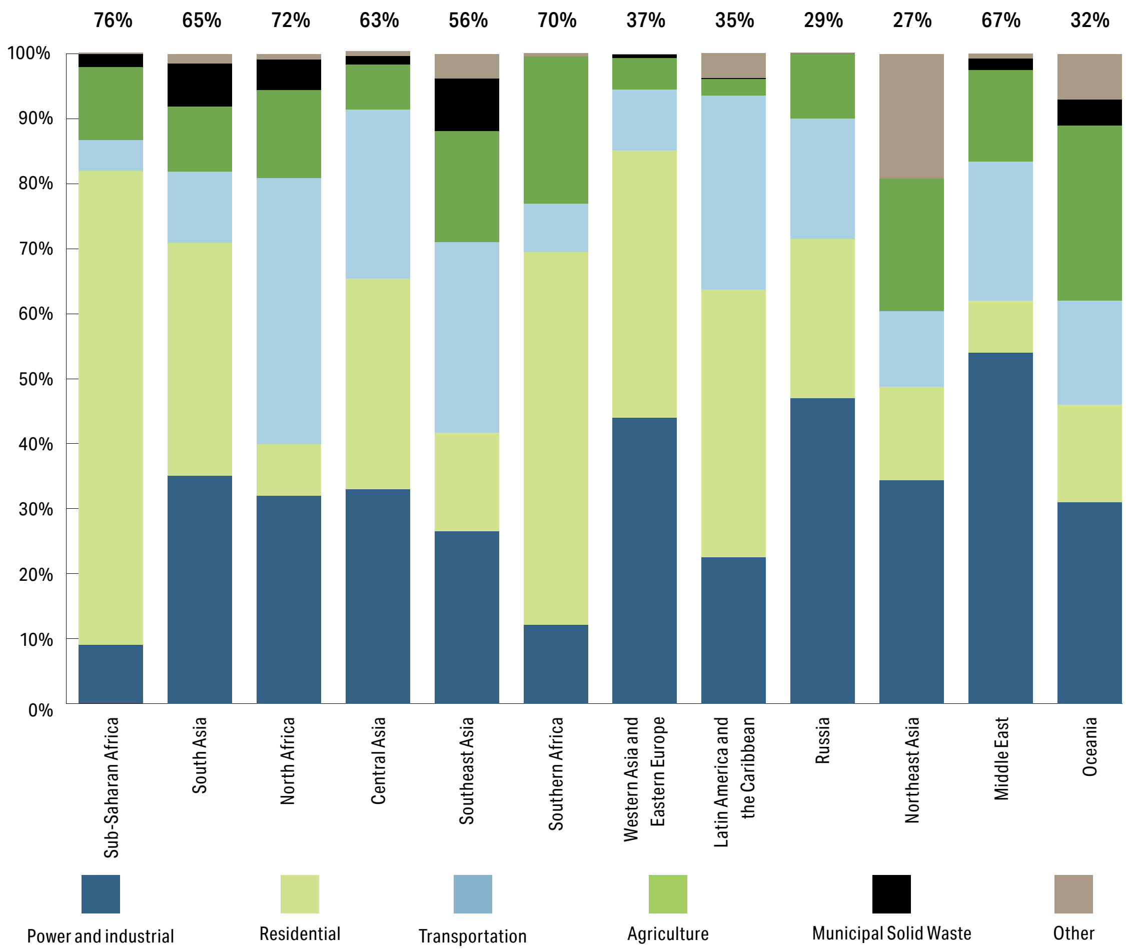
3 = Reduction in exposure due to air quality measures

4 = Total reduction in exposure due to air quality management and energy/climate policies combined

5 = Remaining exposure to $PM_{2.5}$

Source: Original figure for this publication.

Figure 2.3. Sectoral breakdown of additional exposure reductions needed to achieve the Clean Air Targets through integrated policies, by region



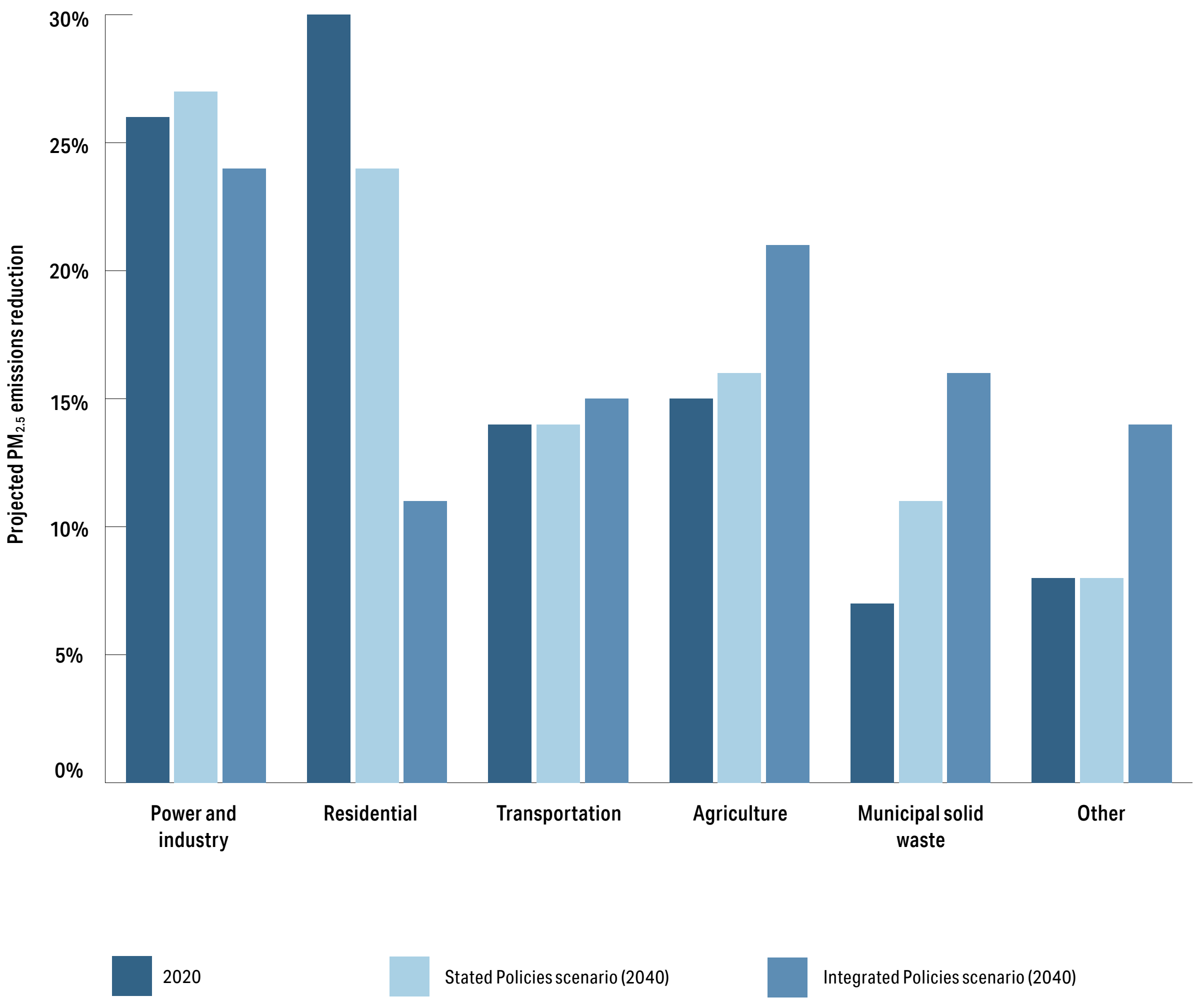
The percentages above each bar indicates the extent of total exposure from anthropogenic sources to be reduced in each region in order to reach the 2040 Clean Air Target.

The colored segments in each bar indicate the sectors in which additional policies and measures emerge as being the most cost effective for achieving the 2040 Clean Air Targets through integrated policies.

Source: Original figure for this publication.

Figure 2.4. Cross-sector interventions would enable the Clean Air Targets to be achieved in a cost-effective fashion

Projected reductions in $PM_{2.5}$ emissions by sector under the Stated Policies scenario and Integrated Policies scenario in 2040, compared with 2020 data



Source: Original figure for this publication.

2.2 COOKING AND RESIDENTIAL HEATING

The residential heating and cooking sector—the source of about a third of anthropogenic $PM_{2.5}$ emissions globally—will play a key role in reducing air pollution exposure by 2040, and is important in Sub-Saharan Africa, South Asia, Central Asia, West Asia and Eastern Europe, and Latin America and the Caribbean. Reducing air pollution from residential heating and cooking sectors will require the reduction or elimination of dirty fuel use (such as solid fuels and kerosene) by moving to cleaner fuels (for example, natural gas and liquified petroleum gas); upgrading technology to achieve efficient energy conversion; and scaling up investments in better insulated buildings and homes.

The burning of solid fuel in households is the greatest anthropogenic source of chronic exposure to $PM_{2.5}$ in many low- and middle-income countries. Solid fuel combustion includes traditional cooking (as practiced in many parts of Africa, Asia, and Latin America) and cooking with coal/briquettes or other biofuels (as is often done in Eastern Europe and Central/East Asia). In 2022, 2.1 billion people across the globe were still cooking with traditional polluting fuels and inefficient stove technologies (IEA et al., 2024). Personal exposure to $PM_{2.5}$ is notably higher among populations that rely on solid fuels for cooking and domestic purposes, with traditional wood stove users being exposed to a 24-hour average of nearly 140 $\mu g/m^3$ (Shupler et al., 2018). Because higher income is a strong driver of the adoption of clean cooking practices, lower-income groups in low- and middle-income countries (LMICs) rely heavily on historically affordable fuels such as wood and charcoal (ESMAP, 2020). Globally, the use of solid fuels is relatively higher in rural and remote areas than in urban areas, both in regions with lower access to clean cooking options (such as Sub-Saharan African) and in regions with the highest access rates (such as Latin America and the Caribbean).

Cooking and interior space heating are key sources of air pollutants other than $PM_{2.5}$., including black carbon, carbon monoxide, PM_{10}, and organic carbon (Peszko et al., 2022). Cooking with solid fuel not only results in household indoor air pollution but is also a significant contributor to ambient air quality. Cooking practices have been found to be responsible for about 12 percent of ambient $PM_{2.5}$ exposure worldwide (Chowdhury et al., 2023). Improving access to clean cooking stoves at the household level could therefore be a powerful tool for improving ambient air quality—particularly in high-density, low-income areas—while also bringing about various co-benefits such as: (i) improving health outcomes, especially for women and children, due to reduced exposure to household air pollution; (ii) contributing to climate mitigation; and (iii) reducing deforestation rates in areas where biomass is the dominant fuel.

Integrating clean cooking in air-pollution reduction strategies could optimize resources and accelerate progress towards reaching healthy ambient air pollution levels. While air pollution strategies typically concentrate on urban areas with high $PM_{2.5}$ concentrations, adopting multisectoral air pollution reduction strategies could help to identify key sectors for improving ambient air pollution in understudied settings such as peri-urban and rural areas in LMICs, where a high reliance on traditional polluting stoves is prevalent (World Bank, 2021a). The transition towards cleaner cooking services involves replacing traditional stoves and burners with improved cookstoves and modern, energy-efficient services. Transitioning towards these technologies is expected to lower $PM_{2.5}$ and carbon monoxide emissions while improving indoor air quality, with modern, energy-efficient services being more impactful than improved cookstoves. In some air pollution hotspots, including South Asia, it is estimated that transitioning to modern, energy-efficient services could be the only option to reach healthy ambient air pollution levels because they produce minimal $PM_{2.5}$ and have the highest combustion efficiency (McDuffie et al., 2021; Chowdhury et al., 2023). Moreover, adopting and enforcing emission standards for cooking stoves is crucial for ensuring that clean cooking contributes to improving air quality and health. Using low-quality stoves that emit excessive pollutants would negate the benefits of clean cooking while overestimating air quality improvements.

Electrification plays a key role in reducing air pollution from cooking—as long as the electricity is from clean sources. When considered at the point of use, electric stoves and cookers are a superior option because their $PM_{2.5}$ and CO_2 household emissions are minimal. However, electric cooking requires an adequate, reliable, and affordable electricity supply that should stem from clean fuel sources to align with clean air objectives. In 2022, 550 million people globally used electricity for cooking, while some 2.1 billion people lacked access to clean cooking solutions (IEA et al., 2024). About 2 billion people with access to some form of electricity continue to rely on traditional cooking solutions (Coley et al., 2021). The potential of electric cooking has not been fully unlocked, even in most developed countries, where LPG and natural gas continue to be used for cooking due to capital investment gaps and challenges linked to affordability and behavioral change.

Leveraging natural gas and LPG for cooking will lead to significant clean air improvements, despite still producing CO_2 emissions (though at reduced levels relative to solid fossil and biomass fuels). Both natural gas and LPG are considered clean cooking fuels. Gaseous fuels (including LPG, natural gas, and biogas fuels) are used as the main cooking fuel by about 60 percent of the global LMIC population (4 billion; IEA et al., 2024). Replacing solid biomass with electricity, natural gas, or LPG could therefore benefit both human health and the climate by reducing GHG and black carbon emissions (Floess et al., 2023). However, transitioning to natural gas and LPG may result in decreased exposure to $PM_{2.5}$ but increase CO_2 emissions, highlighting the importance of contextual considerations and appropriate implementation (World Bank, 2022a). Butanization policies (which promote butane gas or LPG through subsidies) are popular in LMICs to increase energy access and affordability while tackling deforestation. However, despite improvements in the affordability of gas, items relating to the use of gas (such as stoves and canisters) still require upfront costs. This implies that the fuel subsidy could be absorbed by high-income quintiles. Moreover, LPG is dependent on market prices. This price volatility may heavily impact national budgets, which could result in the termination of butanization schemes. This, in turn, could lead to millions of households switching back to solid fuels for cooking and reversing air quality improvements (IEA et al., 2023).

Biogas and ethanol fuels offer solutions for rural locations—although in some cultures their uptake can be challenging. In 2021, nearly 123 million people—mostly from Asia—used biogas for cooking. Africa has also seen growth in the use of this fuel in recent years (IRENA, 2022). Biogas from biodigesters generates an optimal fuel for households in rural areas: those with cattle can produce enough organic waste to generate biogas for their own use and to sell. However, biodigesters have high upfront capital costs and require maintenance. (This upfront cost can be justified in various ways, provided there is enough gas for self-consumption to drive savings in energy costs over a reasonable payback period.) Moreover, within certain cultures and communities, biodigesters are not well accepted because they are considered "unclean". Like biogas, ethanol is a fuel that minimizes the health risks of indoor pollution. Africa is the biggest producer and consumer of ethanol for cooking, with the acceptance of bioethanol steadily increasing, especially in peri-urban areas. Ethanol use is also gaining momentum in parts of Latin America, especially Haiti and Brazil (Hosier et al., 2017). Developing biogas for clean cooking requires an enabling environment and resources to develop livestock supply chains to ensure an affordable and reliable supply of organic waste.

Improved cookstoves—while suboptimal in terms of health gains—offer a partial solution for reducing air pollution exposure levels. The WHO's Air Quality Guidelines recommend that, in cases where clean fuels are not available or accessible, only high-performing improved cookstoves that meet certain standards should be promoted. When equipped with secondary combustion, insulated chambers, and/or fans, the combustion efficiency of improved cookstoves can be improved, reducing $PM_{2.5}$ exposure (WHO, 2014). However, the health impact is not directly proportional to the level of exposure and may only represent an 11 to 12 percent improvement (World Bank, 2022a). Low-quality improved cookstoves may even increase air pollution levels, pointing to a need for standards and labels in the production of improved cookstoves.

Box 2.1. The true cost of heating in regions with cold winters

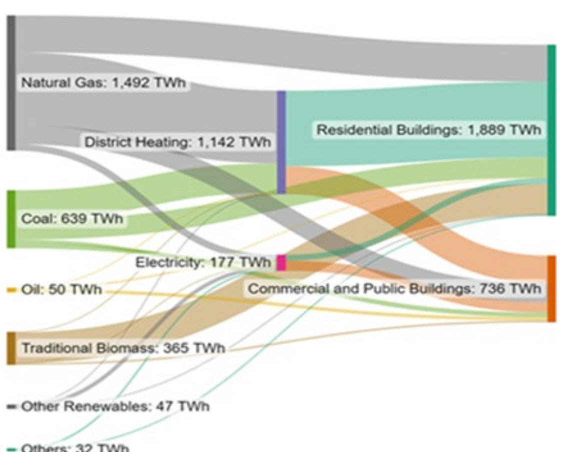
Heating is critical to life and livelihoods in regions affected by long and cold winters. In Europe and Central Asia,[i] interior heating represents 24 percent of the total regional energy demand, of which about 72 percent stems from the residential sector and the remainder from commercial and public buildings. Interior space heating still relies heavily on fossil fuels (especially natural gas and coal) and traditional biomass (predominantly firewood). About 83 percent of space heating in the region is delivered from fossil fuels (Figure 2.5).[ii] After disaggregating district heating and electricity, interior space heating demand is supplied by natural gas (57 percent), coal (24 percent), traditional biomass (14 percent), oil (2 percent), other renewables (2 percent), and other fuels (1 percent). Therefore, almost all the demand (about 95 percent) is supplied by natural gas, coal, and traditional biomass (World Bank and ESMAP, 2023).

East and Central Asia's dependence on fossil fuels and biomass for heating is compounded by an aging and energy-inefficient building stock. Heating residential, commercial, and public buildings in the region releases 1,499 kilotons (kt) of $PM_{2.5}$, 227 kt of nitrogen oxides, and 776 kt of sulfur oxides each year (Figure 2.6).[iii] Coal and biomass make up most of the $PM_{2.5}$ emissions and contribute significantly to nitrogen oxide (43 percent for coal and 28 percent for biomass) and sulfur oxide levels (90 percent for coal and 1 percent for biomass) (World Bank and ESMAP, 2023).[iv] Thus, as in residential cooking, shifting away from solid fuels (coal and biomass) is the preferred route to improved air quality. Reducing the use of liquid fossil fuels will reduce nitrogen oxides and sulfur oxides, although natural gas does contribute to nitrogen oxide production, especially if the operation of the appliance is poorly controlled.

Cost pressures and financial viability concerns generate trade-offs between affordability and pollution abatement. In urban areas in East and Central Asia, most households heat their homes with district heating, electricity, or gas boilers, while in rural areas most households rely on firewood or coal stoves and boilers. About 30 percent of the region's population is served by district heating utilities, which depend heavily on fossil fuels

Figure 2.5. More than 80 percent of space heating in East and Central Asia derives from fossil fuel

Sources and scale of interior heating in East and Central Asia, by fuel

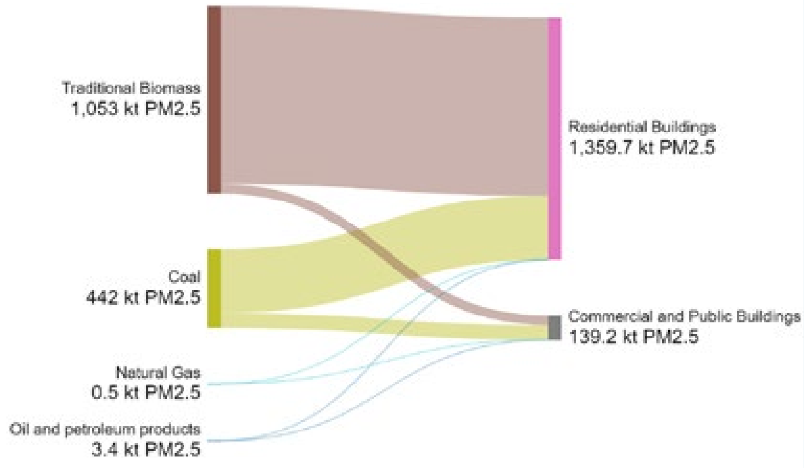


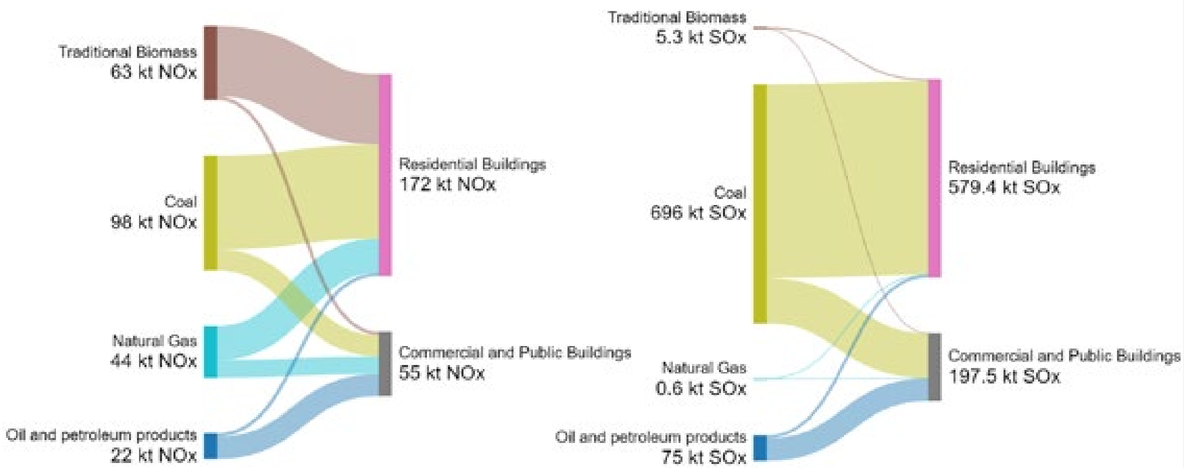
Source: Sankey diagrams produced by World Bank using data in World Bank, 2023c.

Figure 2.6. East and Central Asia's heating sector is a significant source of air pollutants

Estimated interior $PM_{2.5}$, nitrogen oxide (NO_x), and sulfur oxide (SO_x) emissions in East and Central Asia from individual heating systems, by fuel

Source: Sankey diagrams produced by World Bank using data in World Bank, 2023c.





(97 percent) and suffer from aging infrastructure and poor financial viability. As a result of these inefficiencies, heating is unaffordable, with about 34 percent of residents spending 10 percent or more of their average monthly expenditure on energy bills—a typical threshold for energy poverty. When heating prices become unaffordable—as witnessed during the recent energy crisis—households are left with two unappealing choices: reduce the heating levels or revert to dirtier, cheaper fuels.[v]

i The World Bank's East and Central Asia region includes several European Union member states (Bulgaria, Croatia, Poland, and Romania), the Western Balkans (Albania, Bosnia and Herzegovina, Kosovo, Montenegro, North Macedonia, and Serbia), Türkiye, Eastern Europe (Belarus, Moldova, and Ukraine), Russia, the Southern Caucasus (Armenia, Azerbaijan, and Georgia) and Central Asia (Kazakhstan, Kyrgyz Republic, Tajikistan, Turkmenistan, and Uzbekistan).

ii Commercial and public building space heating demand was estimated from the total energy consumption of such buildings. Space heating for residential buildings was calculated using various country-specific sources. The data is largely based on two sources: (i) data from surveys on the share of dwellings relying on different heating fuels (survey data); and (ii) data from energy balances providing the percentage of energy space heating coming from different fuels/sources (energy data).

iii Indirect emissions from district heating and electricity were not considered.

iv These emissions include burning solid and liquid fuels on site and from electricity and heat production due to space heating. While fossil fuels use for space heating in all cases leads to high emissions, electricity use for heating is more varied, with some countries (for example, Albania, Georgia and Tajikistan) having very low grid emissions factors due to a high share of hydropower, while others (for example, Kazakhstan and Poland) show high grid emissions factors due to the high share of coal use for power generation.

v World Bank and ESMAP, 2023.

Most clean cooking solutions can be delivered by the private sector. The aim of policies should therefore be to create an enabling environment for investments in cooking technologies and fuels. The private sector can advance clean cooking by marketing and promoting technologies, creating distribution networks, and making products accessible and more affordable. In parallel, public policy could seek to minimize uncertainties and risks for both private investors and consumers. This implies setting standards for quality solutions; providing incentives for suppliers; promoting consumer-protection rules; and ensuring social protection for disadvantaged households. Significant improvements in access to clean cooking and ambient air pollution levels require strong inter-institutional coordination between the government, the private sector, and development partners.

Encouraging investments in clean cooking will probably be the most cost-effective tool for achieving clean air but will also require using coordinated instruments. The cross-sectoral nature of clean air and clean cooking creates challenges that can best be addressed through strong coordination with robust monitoring and evaluation. Investments into AQM pollution controls in the Integrated Policies scenario are expected to cost about US$3 trillion. Of this, only 2 percent is expected to be allocated to controlling residential heating and cooking emissions. Carbon credits, results-based financing (RBF), and impact bonds are especially well suited to simultaneously addressing clean cooking and clean air objectives by attracting funding from diverse sources and enabling targeted investments. Impact bonds help manage the risks associated with output mechanisms (such as RBF programs) by providing upfront capital from investors, while RBF and carbon credit mechanisms offer a predictable revenue stream to repay investors based on outcomes achieved. These complementary financing mechanisms foster innovation and experimentation in the design and implementation of interventions, allowing for scalability and replication of successful models across different contexts. Given the huge scale-up needed to achieve universal clean cooking objectives, innovative business models that attempt to replicate successes in other sectors will need to be developed.

Next to household cooking, heating is a notable contributor to $PM_{2.5}$ exposure due to the widespread use of solid fuels. Burning coal and traditional biomass to heat residential and commercial structures releases many pollutants while producing relatively little heat. $PM_{2.5}$ emissions vary significantly depending on the type of fuel and heating system used.

Solutions to abate air pollution from heating are known, but challenges remain. These solutions include: (i) reducing energy demand by implementing household energy efficiency measures (for instance, by improving insulation), (ii) upgrading to more efficient heating solutions and those that use renewable energy, and (iii) using natural gas as a transition fuel when other options are not yet available. However, efficiency and heating upgrades typically entail substantial upfront costs that may lower household interest. Similarly, utilities that are considering district heating investments may be deterred by costs that exceed viability thresholds. Scaling up solutions revolve around tailored financing tools and an ecosystem that involves the public and private sectors, as well as leveraging consumer insights for effective implementation.

2.3 AGRICULTURE

Reducing air pollution emissions from agriculture requires multiple interventions and is particularly important in Sub-Saharan Africa, Southeast Asia, Southern Africa, Northeast Asia, and Oceania. Key interventions are reducing ammonia emission from intensive fertilizer use, improving manure management in large livestock operations, and reducing crop-residues burning. Doing so will require support to ensure farmers have access to suitable technologies and that they are incentivized to use them. Implementing policy actions could further support sustainable agriculture practices.

The agriculture sector is negatively impacted by air pollution. A one percent increase in $PM_{2.5}$ concentration is estimated to lead to a 0.104 percent decline in global agricultural total factor productivity, equivalent to US$5 billion per year (Dong and Wang, 2023). Decreased agricultural productivity due to air pollution has significant economic implications, affecting farmer incomes, food prices, and global food-supply chains. Air pollution also reduces crop yield and quality, which lowers farmers' profits and leads to economic hardship and potential food shortages, particularly in regions that rely heavily on agriculture. These impacts are context-specific and based on factors such as pollutant concentration, crop type, and environmental conditions, which highlights the need for localized research and mitigation strategies.

At the same time, intensive agriculture and unsustainable agricultural practices contribute significantly to air pollution. In 2020, about 15 percent of global exposure to anthropogenic $PM_{2.5}$ air pollution was attributed to the agriculture sector. Intensive fertilizer use and poor manure management, and burning forests to clear land for agriculture all contribute to $PM_{2.5}$ emissions. During field application, the drift of pesticide sprays and the act of spreading fertilizer contribute to airborne $PM_{2.5}$ levels. These applications can also generate $PM_{2.5}$ through volatilization and chemical reactions. Intensive livestock farming produces large quantities of particulate matter— especially $PM_{2.5}$ in the form of dust from feed-handling, bedding materials, and manure—from manure management, feedlots, and animal housing facilities.

The burning of crop residues—a common agricultural practice to clear fields quickly for the next planting season— emits high levels of $PM_{2.5}$. Crop-residue burning is widespread, but it is mostly practiced in South Asia in the rice-wheat crop cycle, where the large quantities of residues produced

Box 2.2.
Case study: Burning crop residues in India

The burning of crop residue is pervasive in northwest India for a variety of reasons, including mechanized harvesting driven by rural labor shortages; groundwater conservation policies that narrow the window between rice harvesting and wheat sowing; policies that favor yield intensification; and ineffective enforcement of no-burn regulations (Hellin et al., 2021).

Reducing the burning of residue requires a multifaceted approach that combines technology, market development, and novel institutional and policy changes. Advanced mechanical seeders enable farmers to plant crops into rice residues without first burning them. Shifts in crop management practices, such as direct-seeded rice and using shorter-duration rice cultivars, contribute to reduced water use and facilitate earlier harvesting, which reduces the need to create air pollution by burning residue. Expanding agricultural extension practices beyond technical training to support social learning of such methods and value-chain development for new technologies could therefore accelerate change.

Diversifying crops away from rice is potentially transformative, especially in northwest India. However, past efforts have largely failed because of subsidies that favor rice, which include free electricity for irrigation and minimum-support-price guarantees for rice procurement. Replacing these subsidies with payments for ecosystem services for reducing air pollution may encourage farmers to grow alternative crops and to adopt no-burn methods. The complex problem of agricultural burning and air pollution will likely only be resolved with coordinated actions to address all these considerations.

In terms of policies to improve crop-residue management, in 2014 India formulated a National Policy for Management of Crop Residue to promote technologies for in-situ management of crop residue and to encourage the productive use of crop residue. More recently, India's government rolled out a crop-residue management scheme costing US$164 million to incentivize farmers in the northern states to quit the practice of burning crop residue. Under this scheme, farmers and farming cooperatives benefit from financial support (80 percent and 50 percent, respectively) for purchasing machines for in-situ crop-residue management. However, there are concerns that smaller, marginalized farmers may not benefit from this incentive scheme because the cost of these technologies remains well beyond their reach, even with the subsidies (Kumar and Singh, 2021). The Indian government has also established a National Clean Air Programme, which includes an extensive drive against open burning to reduce $PM_{2.5}$ pollution by between 20 and 30 percent by 2024. This program has been extended with a target of 40 reduction by 2026 (against a 2017 baseline) in several cities (Ganguly et al., 2020; Manojkumar and Muruganandam, 2025).

Despite the existing regulations, the burning of crop residue has not stopped. Factors affecting this lack of uptake include uncertainty regarding policy implementation, partial enforcement, issues around access to alternative technologies, and a lack of feasible, affordable, and profitable alternatives (Shyamsundar et al., 2019). Crucially, for policies to be efficient, farmers must be involved in the design and implementation process. Besides this, the lack of a database or specific guidelines and policies for the proper management of the residue needs to be addressed (Haider, 2013).

need to be cleared in a short period. Burning is often the lowest-cost option for farmers to dispose of crop residues, which would otherwise involve additional investments in terms of energy and money. Reducing the burning of crop residues will require scaling up sustainable residue management practices by: (i) implementing policies and regulations to ban crop-residue burning; (ii) rewarding sustainable practices through payments for ecosystem services; (iii) promoting the alternative uses of residues such as mulching, incorporating them into soil, or using them for feed; (iv) changing the rice-wheat crop cycle; and/or (v) supporting farmers with adequate technologies and public-awareness campaigns. Scaling these interventions poses several practical, economic, and policy constraints (Box 2.2). The proposed technical solutions should be politically feasible and cognizant of the challenges of reforming policies (especially those that relate to price support or include input subsidies).

Nitrogen emissions are responsible for a large share of $PM_{2.5}$ concentrations. Intensive fertilizer application is the primary source of emissions of ammonia (NH3), contributing to more than 80 percent of total ammonia emissions in many agriculture-intensive regions. Ammonia is a secondary $PM_{2.5}$ precursor, and ammonia emissions from agriculture are responsible for 30 percent of all $PM_{2.5}$ in the United States and India's Ganga Basin; 50 percent in Europe, where good progress has been made tackling other sources; and between 15 and 23 percent in China (Erisman and Schaap, 2004; Behera et al., 2010; Bauer et al., 2016; Han et al., 2020; Wyer et al., 2022). An increase in large-scale intensive agricultural operations, such as concentrated animal feeding operations, has contributed to increasing ammonia emissions (Schultz et al., 2019). The potential effect of this pollutant on human health is also a concern (Naseem and King, 2018; Ge et al., 2020).

Several manure management practices can help reduce air pollutant emissions from livestock operations. Managing livestock emissions requires minimizing the release of gases (such as ammonia and volatile organic compounds), as well as reducing the generation of particulate matter. Specific strategies such as AQM, biofilters, and manure storage and treatment are mostly applicable to large, industrialized farms and mass animal-rearing facilities. However, many of these measures face cost-effectiveness and capacity constraints when applied to small subsistence agriculture.

A range of technologies and practices are available to limit emissions from fertilizers, but their deployment is contingent on supporting farmer uptake. Nitrogen-use efficiency refers to the proportion of applied nitrogen fertilizer that is taken up by crops. Improving this metric is central to reducing fertilizer emissions. Precision agriculture practices can help optimize fertilizer use by drawing on global positioning systems, remote sensing, and soil-testing technologies to ensure that the amounts of fertilizer used are tailored to a crop's needs, so minimizing nitrogen losses to the environment. Enhanced-efficiency fertilizers release nitrogen more slowly, matching the nutrient-uptake pattern of crops. Nitrification and urease inhibitors can also be added to fertilizers to slow down the conversion processes that lead to nitrogen loss. Integrated nutrient management combines organic and inorganic fertilizers to optimize nutrient availability and improve soil health. Crop rotation and cover-crop practices can improve soil structure and fertility, reducing the need for synthetic fertilizers. In addition to adequate regulations and incentives, farmer education and training are key to disseminating and driving these practices.

Pesticide-related $PM_{2.5}$ emissions can be abated through stricter integrated pest management regulations. Implementing stricter regulations on pesticide formulations and application methods, while also implementing policies that encourage the use of less volatile and lower-toxicity pesticides, may help reduce the contribution of pesticides to emissions that form $PM_{2.5}$. Integrated pest management practices include biological controls, crop rotation, and other sustainable agricultural practices to reduce overreliance on chemical pesticides (Gunstone et al., 2021). A reduction in the use of chemical pesticides would, in turn, lower the potential for $PM_{2.5}$ to form. Using precision agriculture technologies can optimize pesticide application, ensuring that only the necessary amounts are used, so reducing the potential for airborne emissions and $PM_{2.5}$ formation (Boonupara et al., 2023).

In addition to improved use of fertilizers and other agricultural inputs, there is a need to focus on soil health. Soil health is the foundation of agricultural productivity and broader ecological balance. Healthy soil supports a diverse microbial community and contains the nutrients essential for robust crops. Various conventional farming practices, such as moldboard plowing, can significantly impact not only soil quality but also air quality (Panettieri et al., 2013). When the soil is turned over, it disrupts microbial habitats and releases dust and particulate matter into the air, increasing health risks to both humans and animals. In addition, bare soil is prone to wind erosion, leading to higher $PM_{2.5}$ levels and worsening air quality. A study in Türkiye's arid Iğdır province showed that wind erosion is a major contributor to particulate matter pollution, especially during the summer. The area experiences frequent dust storms, which are exacerbated by factors like irregular rainfall, high temperature differences, strong winds, and vegetation destruction. Such conditions facilitate the suspension of fine soil particles in the air, significantly affecting air quality (Öztürk et al., 2023).

Various agricultural practices—such as reduced tillage and no-till farming, as well as the use of cover crops—can significantly help rebuild soil health and, in maintaining healthy soil structure, reduce the release of particulates. Incorporating compost or manure can also help enhance soil structure, increase water retention, and improve the resilience of soil against erosion. In addition, strategies like agroforestry and implementing windbreaks with rows of trees or shrubs can significantly reinforce soil stability, minimizing soil displacement and reducing the release of particulate matter into the atmosphere.

2.4 INDUSTRIAL SOURCES AND POWER GENERATION

Addressing air pollution from industrial sources and power generation will be especially critical in South Asia, Northeast Asia, the Middle East, and North Africa. Key interventions include policies to support circular economies; implementing cleaner production technologies combined with stringent and effective measures for industrial air emissions control; and a transition to low-emission energy sources.

Industrial activities release a range of air pollutants, including vapors, aerosols, solid particles, and toxic gases. Industrial operations are also major consumers of energy and significant sources of GHGs. These emissions—which include CO_2, sulfur oxides, nitrogen oxides, carbon monoxide, volatile organic compounds, and particulate matter—are released into the atmosphere during various industrial processes, primarily through the combustion of fossil fuels.

Governments have enacted various regulations and policies to address air pollution by reducing emissions from industrial activities. These policies are tailored to each country's specific environmental challenges, industrial landscape, and socioeconomic context. They often include measures such as setting emission standards, implementing pollution-control technologies, promoting cleaner production processes, incentivizing the adoption of renewable energy, and establishing monitoring and enforcement mechanisms to ensure compliance. National policies are crucial for fostering conditions conducive to adopting cleaner, more efficient, and competitive production methods; driving economic growth; and facilitating a greener transformation.

The European Union (EU) Industrial Emissions Directive stands as a prime example of a comprehensive legal framework for controlling industrial air emissions. It employs a comprehensive approach to prevent and manage pollution from various industrial sources that have significant pollution potential. The directive mandates the use of Best Available Techniques by establishing reference documents that set emission limit values for all major emitting industries. This approach is mirrored in other parts of the world, reflecting a global commitment to environmental protection. Initiatives such as the US Clean Air Act, China's Air Pollution Prevention and Control Action Plan, and India's Air (Prevention and Control of Pollution) Act collectively represent a global movement towards adopting stringent and effective measures for industrial air emissions control, leveraging the concept of best available techniques to achieve cleaner air and a healthier environment.

On the other hand, significant technological progress has provided industrial facilities with innovative tools and solutions to effectively tackle pollution. These advances encompass a wide range of strategies and technologies to reduce emissions, minimize waste generation, and enhance overall environmental sustainability within industrial operations. Reducing air pollution in manufacturing requires a multifaceted approach that integrates various measures for emissions reduction and pollution control, including:

- **Implementing cleaner production technologies.** Adopting cleaner production technologies and processes that prioritize energy efficiency, waste reduction, and emission prevention can significantly decrease air pollution from manufacturing operations.

- **Using low-emission energy sources.** Transitioning to low-emission energy sources such as natural gas, renewable energy (solar, wind, or hydro), or biomass could reduce GHG emissions and air pollutants associated with energy-intensive manufacturing processes.[21]

- **Optimizing combustion processes.** Implementing advanced combustion technologies—such as ultra-low nitrogen oxide burners and staged combustion—can improve fuel efficiency and reduce emissions of nitrogen oxides, sulfur oxides, and particulate matter from boilers, furnaces, and other combustion sources.

- **Installing pollution control equipment.** Installing effective pollution control equipment such as electrostatic precipitators, fabric filters, scrubbers, and catalytic converters capture and treat airborne pollutants before they are released into the atmosphere.

- **Implementing process changes and redesign.** Reducing emissions through initiatives to change and redesign processes (for example, by optimizing raw material usage, modifying production techniques, and minimizing waste generation) can help mitigate air pollution from manufacturing activities.

- **Promoting resource efficiency and recycling.** Embracing resource-efficient practices such as material recycling, closed-loop manufacturing, and waste minimization can reduce the consumption of raw materials, energy, and water, thereby lowering emissions associated with manufacturing processes.

By implementing these measures in a comprehensive and systematic manner, manufacturers can effectively reduce air pollution emissions, improve environmental sustainability, and contribute to healthier communities and ecosystems. In doing so, they can also stay competitive and contribute to their countries' climate change goals. However, the uptake of these measures and technologies—especially by small and medium-sized enterprises—has been limited due to several barriers, including:

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21 For some industrial processes (for instance, those using heat), no viable solution without fossil fuel combustion exists. In these cases, bridge technologies like natural gas and the implementation of abatement technologies currently play an important role to reduce air pollution.

- **Financial barriers** such as the large upfront capital expenditure required for equipment or process changes and limited access to affordable financing.

- **Economies of scale in pollution control investments** due to smaller production volumes and limited market reach. The unit cost of implementing pollution control measures may be higher for small businesses, making it financially challenging to justify investments in retrofitting and pollution reduction.

- **Competitive pressures.** Small businesses operating in highly competitive markets may prioritize short-term financial goals over long-term sustainability and environmental stewardship. These projects often compete for limited resources with other internal business priorities that are essential for revenue generation. Fear of losing market share or customers to competitors who prioritize price over environmental performance might deter small businesses from investing in pollution control measures.

- **Technical barriers.** Small businesses may lack the in-house expertise and specialized knowledge required to identify, select, and properly implement pollution control measures.

- **Lack of access to information and support.** Small businesses may lack access to market-relevant information, technical assistance, and support services related to pollution control and environmental management.

- **Risk aversion and uncertainty.** Small businesses may be hesitant to invest in pollution control measures due to perceived risks, uncertainties, and potential disruptions to their operations. Concerns about the return on investment, payback periods, and financial viability of pollution reduction initiatives may also discourage them from taking proactive action.

- **Weak policy frameworks.** The absence of (i) regulatory frameworks that set emissions and air quality targets for specific sectors, (ii) well-funded government institutions, and (iii) economic incentives combined with financial and technical support undermine the adoption and financing of clean technologies.

Overcoming these barriers requires tailored support mechanisms, including financial incentives, technical assistance programs, regulatory frameworks, risk-sharing mechanisms, blended finance structures, targeted credit programs, and capacity-building initiatives specifically designed for the needs of small and medium industries and businesses (see Chapter 3). Collaborative efforts involving governments, industry associations, financial institutions, and community organizations are crucial for promoting sustainable practices among small businesses. Given that large point sources often have clear revenue streams and proven business models, governments can leverage targeted public co-financing, risk-mitigation tools, and robust monitoring, reporting, and verification systems rather than relying solely on direct subsidies to incentivize cleaner production. The World Bank has extensive experience in supporting countries to tackle industrial air pollution through comprehensive financial and technical solutions.

Box 2.3.
Chinese cities: An early focus on industry

Between from 1997 to 2012, the average PM_{10} concentrations in Chinese cities went down by about 45 percent due to an overhaul of air quality management policies in 2000. Policy changes included the implementation of an emission permit and fee system; reinforced vehicle measures; and urban dust measures. Furthermore, the government required key cities to develop plans for meeting air quality targets on a fixed timeline. To measure progress, the country's air quality monitoring system (measuring ambient PM_{10}, NO2, and SO_2 levels) was expanded to about 613 cities.

However, China's growing economy has led to increased industrial and vehicle emissions. There have been some severe pollution episodes, and previous policies mean that easy fixes have already been implemented. Based on new regulations, China is now moving forward by tightening existing standards, expanding its monitoring network to include $PM_{2.5}$, CO, and O3 throughout all its cities, and establishing new standards for these pollutants. These standards are linked to stringent new action plans, which are expected to be rolled out on fixed timelines.

2.5 TRANSPORTATION

Nearly 15 percent of global $PM_{2.5}$ exposure is caused by the transport sector, even though this varies greatly by location and context. Addressing transportation emissions is important particularly in South Asia, Northern Africa, Middle East, Central Asia, and Southeast Asia. The key actions to reduce air pollution include integrated transport planning to reduce motorized travel; promoting a shift from personal vehicles to public transport and non-motorized modes; and improving vehicles' fuel efficiency and the adoption of electric vehicles.

Transport is the world's fastest-growing source of energy-related carbon emissions: more than 60 percent of global oil consumption and roughly a quarter of energy-related carbon dioxide (CO_2) emissions are attributed to transportation (IEA, 2021b). The sector also contributes significantly to $PM_{2.5}$ and PM_{10} pollution, as well as nitrogen oxide and sulfur oxide emissions (Dulal and Timilsina, 2011; Oliva and Hidalgo Guerrero, 2019). Air pollution costs contribute to the overall negative effects of congestion caused by traffic: in Beijing, for example, the cumulative impact of motorized transport (including air pollution, accidents, and noise) cost between 7.5 percent and 15 percent of the city's GDP (Creutzig and He, 2009).

The transition to electric passenger vehicles can significantly reduce emissions of the most harmful particulate matter, potentially by up to 10 times per passenger-kilometer traveled (Briceno-Garmendia et al., 2023). The higher initial investment required for purchasing electric vehicles is often counterbalanced by reduced lifecycle costs and the advantages of mitigating externalities. About US$4 trillion investment in public buses, trains, and rail infrastructure is projected to yield US$1 trillion in annual benefits by 2030, with a net present value of US$19.6 trillion. For many countries, the shift to electric mobility is economically attractive just for the lower operating costs, because electric vehicles are much more energy-efficient than conventional vehicles, typically saving about US$10,000 in energy costs over the lifespan of a four-wheeled vehicle (Briceno-Garmendia et al., 2023). When the benefits of reducing externalities are considered, the number of countries for which electric mobility looks economically attractive increases significantly. However, electric vehicle mobility faces several challenges, including the need for a reliable, renewable power supply and faster wear on tires (due to electric vehicles being heavier than traditional fuel vehicles) leading to increased microplastic pollution and waste. This underscores the need for a multisectoral approach.

Beyond electrification, measures that aim to Avoid, Shift, and Improve emissions can deliver substantial gains (World Bank, 2014). Such measures include:

- **Avoid.** Address the overall demand for transport activity by reducing the need for travel, both in terms of the number of trips that people make and the length of each of these trips. Good land-use planning, focused on developing compact cities and mixed land use, and integrated transport planning can contribute to reducing the need for motorized travel and the length of the trips that need to be made. Policy changes for effective land use management can bring opportunities, activities, services, and goods closer to the people and prevent urban sprawl.

- **Shift.** These actions aim to persuade people to move away from personal motor vehicles to public transport and non-motorized modes, which are more efficient in terms of the urban space they occupy, the amount of fuel they consume, and the amount of pollution they generate. Actions promote a shift of passenger or freight trips from more carbon-intensive modes to less carbon-intensive modes. Because no single mode can address all transport needs, implementing low emissions zones and improving public and non-motorized transport options can be effective for shifting urban trips away from low-occupancy private vehicles.

- **Improve.** These actions seek to reduce the negative impacts of motorized travel that inevitably persist despite implementing Avoid and Shift measures. These actions address the efficiency and quality of vehicles, operations, and fuels by improving the flow of traffic, the fuel efficiency of motor vehicles, and the quality of fuel used—along with the adoption of more stringent emission standards. Vehicle retirement or scrappage schemes can financially incentivize owners to take their older, more polluting, or less efficient vehicles off the road and substitute them with vehicles with modern, efficient emission controls. It is especially important to improve motorized transport and focus on vehicle entry policies in LMICs, where vehicle fleets are often older and create more pollution.

Avoid, Shift, and Improve strategies have already proven their effectiveness in major agglomerations across the globe. This framework for transport connects to broader urban planning reforms and transit-oriented development principles. Urban planning can reduce the need for motorized transportation by minimizing both the number and length of trips needed through better land-use planning, more compact cities, and mixed land-use development—core elements of transport-oriented development. Successfully implemented Avoid, Shift, and Improve strategies in cities such as Tianjin, China, and Paris, France, have led to decreases in both noise pollution and emissions.

Box 2.4.
Mexico City: An early focus on transport

Mexico City has cut vehicle emissions by strengthening regulations and embracing public transportation.

Mexico City's population had grown from fewer than 3 million in 1950 to about 20 million in 2011, creating a traffic-choked urban sprawl. The increase in emissions was worsened by a geography that trapped pollutants, and led to the United Nations Environment Programme declaring, in 1992, that Mexico City had perhaps the world's worst air pollution.

By 2010, however, Mexico had halved concentrations of most pollutants. Particulate matter had dropped by 70 percent and airborne lead concentrations had dropped by more than 90 percent, even as the number of cars in the city doubled. To achieve these results, Mexico City cut emissions from vehicles by mandating the installation of catalytic converters in automobiles, removing lead from gasoline, reducing the sulfur content of diesel, and strengthening a vehicle inspection program designed to reduce emissions from old, obsolete, and/or poorly maintained vehicles. The city also embraced public transportation by adding a new hybrid-electric line to its metro system.

The government has also taken steps to remove regressive and inefficient fossil fuel subsidies that in 2011 were equivalent in value to 1.15 percent of its GDP. Given that Mexico's transport sector emits a third of the country's greenhouse gas emissions, it is expected that adopting more modern fuel and emission standards, in addition to the reduction in gasoline subsidies, will lead to reduced air pollution, which will, in turn, reduce health damages from air pollution, which currently costs 1.5 percent of GDP.

Box 2.5.
The Complementarity of Standards and Fiscal Incentives in Improving the Quality of Used Vehicles in Mauritius

Mauritius is a small island country with many urban transport challenges, including congestion, air pollution, and traffic accidents. To address these challenges, the country has taken a comprehensive approach to managing used vehicles that enter the country that includes introducing complementary standards and processes, and fiscal measures:

Standards and processes. The age limit for imported used vehicles is set at a maximum of three years from the date of manufacture. Additionally, there is a mandatory, comprehensive verification and inspection process upon the arrival of used vehicles. This process requires several documents—including an import permit, an export certificate, previous inspection certifications, and proof from the export company that the vehicle is not a product of theft—to confirm the vehicle's authenticity and date of import.

Fiscal measures. Mauritius has implemented a vehicle progressive excise taxation scheme for used vehicle imports based on engine size, capacity, and CO_2 emissions, with vehicles up to 550 cc exempt from excise tax. Used hybrid and electric vehicles are exempt from this tax. In addition, vehicle owners are required to pay a yearly road tax based on the type of vehicle and the engine size.

These policies have been effective, leading to a younger and cleaner vehicle fleet. The average age of vehicles is now under five years. The average fuel efficiency has improved from 7 liters per 100 kilometers in 2005 to 6.6 liters in 2013, and down to 5.8 liters in 2014. Hybrid vehicle sales also rose from 43 units in 2009 to 14,754 in May 2020.

Box 2.6.
Public-private partnership and an innovative leasing scheme promote adoption of electric buses in Chile

Chile does not have local e-bus manufacturing. The introduction of e-buses was facilitated through a public-private partnership between the Ministry of Transport and Communications and the energy companies Enel and ENGIE. These energy firms financed the initial acquisition of e-buses manufactured in China, as well as the electric charging infrastructure, by establishing leasing contracts with private bus operators. This involved monthly payments for fleet provision, charging infrastructure, and energy supply. The government played an important role in the transition to e-buses by facilitating the process, reducing approvals and authorization times, and supporting the planning and regulation of the bus system. While the government was responsible for collecting and distributing revenues, the operation of the bus lines was managed by six private companies. The operational model was based on two different types of contracts for the operations, infrastructure, and assets, which distinguished between the provision of the fleet and the ownership and operation of depots, as well as the maintenance of the buses.

2.6 MUNICIPAL SOLID WASTE

Municipal solid waste contributes substantially to $PM_{2.5}$ concentrations in South Asia, Southeast Asia, and China. Improving the management of solid waste can reduce air pollution and help mitigate global climate change. Priority interventions include implementing measures to stop open burning of municipal waste in urban areas and preventing fires at dumpsites; rolling out integrated solid waste management programs including ensuring the vehicle fleet is updated and fuel is high quality; and developing policies that support the circular economy by encouraging increased recycling.

$PM_{2.5}$ emissions from municipal solid waste accounted for 7 percent of global exposure to anthropogenic $PM_{2.5}$ emissions in 2020 and are expected to increase to 11 percent globally by 2040 under the current policy landscape. Open dumping, landfills, and poor organics management contribute to anthropogenic methane emissions, while the open burning of municipal solid waste is a significant contributor to $PM_{2.5}$ and black carbon emissions.

The open burning of waste is the overwhelming contributor of $PM_{2.5}$ pollution in many developing countries. For example, 71 percent of $PM_{2.5}$ in Accra, Ghana, comes from the open burning of waste (Naidoo et al., 2021). In general, a larger share of waste is openly burned in low- and low-middle-income countries such as Cambodia (where 15 percent of waste was openly burned in 2004), Indonesia (26 percent was burned in 2019; the Republic of Indonesia, 2021), and Tanzania (23 percent in 2012). While these are national statistics, waste generation is higher per capita in more urbanized areas, where solid waste management is typically a municipal responsibility (Kaza et al., 2018). Establishing an integrated solid waste management system—starting with collection and ending with the safe disposal or recycling of waste—in combination with regulations and enforcement could reduce such air pollution. A system that includes recycling facilities would also improve operations at the point of disposal (Kaza et al., 2018).

Burning waste releases not only particulate matter and GHGs but also toxic gases, depending on the waste being burned. The health impacts of burning solid waste are not limited to the emission of particulate matter. Studies show that people working in and living near a dumpsite in Accra where electronic waste was regularly burned were exposed to high levels of the compounds used in making electronics in the ambient air. The risks of such exposure are particularly high for newborn babies and pregnant women because heavy metals in the air and dust—as is associated with burning certain kinds of waste—can result in neurodevelopmental disorders (Daum et al., 2017).

Reductions of $PM_{2.5}$ emissions from open burning and fires at poorly managed disposal sites have a number of other environmental co-benefits including improved water and soil quality at or near dump sites, improved waste recycling, and decreased GHG emissions. Options to reduce $PM_{2.5}$ emissions from municipal solid waste by reducing the amount of trash being burned include efficiently collecting and safely disposing of waste before it is burned; encouraging separation of waste at the source to support circular economies through increased waste recycling; and implementing material efficiency strategies. Increasing the processing and treatment of waste can support a reduction in waste overall and remove certain waste streams, such as plastics. In addition, $PM_{2.5}$ and black carbon emissions resulting from old collection vehicles and poor fuel quality can be addressed by systematically improving the vehicle fleet and fuel choice.

Options to improve dumpsite operations include compacting waste, applying a daily cover, installing landfill gas collection and use systems, preventing informal waste pickers or workers from burning waste, maintaining a stockpile of materials and equipment to prevent the spread of fire, and reclaiming unused areas prone to combustion. A granular analysis of dumpsite hotspots for fires and degradation risks is recommended to prioritize those needing risk mitigation first. This requires establishing standard operating procedures, providing operators with training, and supporting the revision of regulations as needed. Increased monitoring and enforcement capacity should be scaled over time. Once full, dumpsites should be remediated and closed using appropriate gas-collection and utilization systems (if viable) or safe venting and flaring arrangements to prevent fire risks. New landfills should be constructed and operated in line with international standards for sanitary landfills, including the installation of landfill gas capture and utilization systems to prevent fire hazards.

For diffused, smaller-scale waste burning in rural and peri-urban areas, necessary measures include providing adequate infrastructure and services for waste collection; ensuring safe disposal options; building awareness among communities on the health impacts of open burning of waste; and building capacity with waste collection staff to prevent local burning. Poor waste collection is the most important driving factor for open dumping and burning. To address this issue, efforts should be made to improve the efficiency and footprint of waste collection and management services to all parts of the cities and towns. An inventory of potential waste-burning locations should be completed to assess service provision challenges and identify where infrastructure, monitoring, and other services are most needed. Based on this, targeted interventions may be implemented. Additionally, local communities may be sensitized to the risks of open burning through appropriate awareness programs. Analysis tools such as behavioral insights may also be deployed, so that waste burning is prevented in a sustainable manner.

2.7 URBAN SOLUTIONS

The combination of high levels of air pollution and large populations make city-level interventions essential for reducing global exposure to particulates. Key interventions that are relevant to all regions include investing in air quality monitoring and information; specifically targeting vulnerable groups during air quality emergencies; enforcing standards; and ensuring that urban development plans limit sprawl.

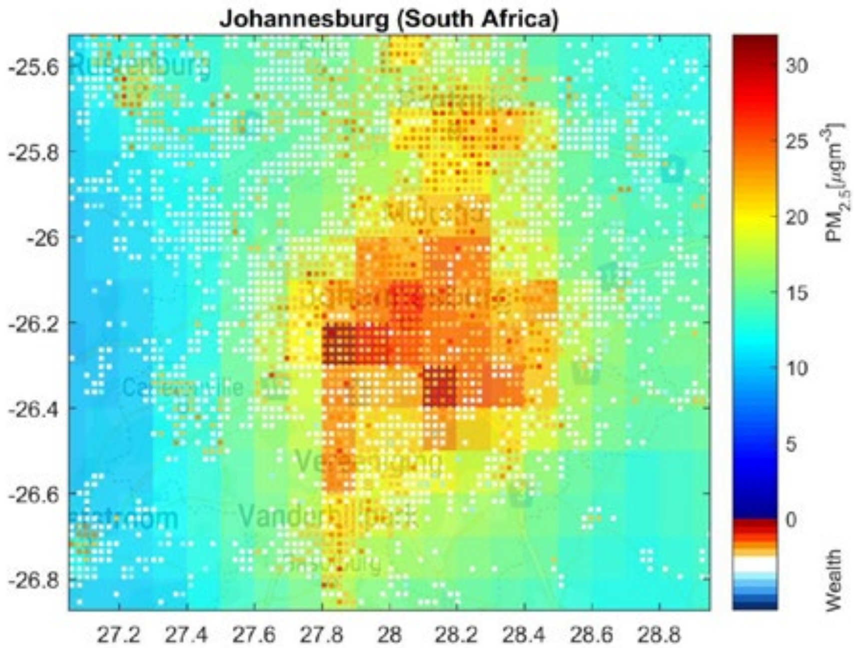
The share of the world's population living in towns and cities has been rising steadily—a trend that is projected to continue until 2050. Some 56 percent of the global population lived in cities and towns in 2020, accounting for two-thirds of global energy consumption and more than 70 percent of CO_2 emissions—despite the fact that about one in three urban inhabitants dwell in informal settlements without adequate access to basic services (Ritchie and Roser, 2019). The share of the global population living in towns and cities is expected to rise to almost 70 percent in 2050, and to grow especially fast in Sub-Saharan Africa and South Asia (UNDESA, 2019).

Cities spatially concentrate polluting activities and people, resulting in both high pollution and high exposure levels. Figure 2.7 shows the overlap between the concentration of wealthy population and air pollution in Johannesburg, South Africa, demonstrating that the wealthier part of the population lives mainly concentrated in cities where the $PM_{2.5}$ concentrations are higher. Polluting activities in urban areas include industries, transportation, construction, and the burning of non-agricultural waste, among other contributing factors.

Cities in low- and middle-income countries have worse air pollution than cities in high-income countries. A recent World Bank study of more than 10,000 cities globally found that cities in lower-middle-income countries had the highest concentrations of $PM_{2.5}$, followed by upper-middle- and low-income countries. High-income countries have the lowest concentrations (Figure 2.8). This suggests that air quality first deteriorates and then improves again as countries become wealthier. Concentrations in lower-middle-income countries are double those in high-income countries, on average (Mukim and Roberts, 2023).

Larger and less compact cities have more air pollution. The same recent World Bank study found that $PM_{2.5}$ emissions from residential buildings and transportation activities are higher in more populous cities, controlling for the GDP per capita of the country in which the city is located, its built-up area, and other variables (Figure 2.9). The study also observed that more compact cities have significantly lower $PM_{2.5}$ emissions from these sources.

Figure 2.7. Overlap between pollution and wealth in Johannesburg, South Africa

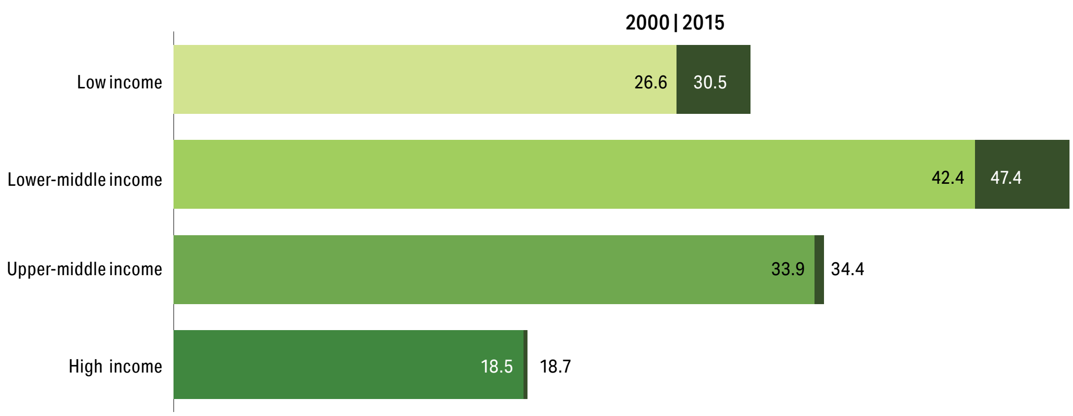


The small dots represent population wealth and the larger colored squares represent $PM_{2.5}$ levels.

Source: IIASA (GAINS model).

Figure 2.8. Cities in low- and middle-income countries have worse air pollution than cities in high-income countries

Average $PM_{2.5}$ concentrations across cities, by country income group, 2000 and 2015, in microgram per m^3



The graph shows the weighted average $PM_{2.5}$ concentration for cities in each income classification, with weights given by city populations.

Source: Mukim and Roberts, 2023. Original World Bank figure based on data for 10,303 cities from the European Commission's Global Human Settlement Urban Centra Database R2019,* with weights given by city populations.

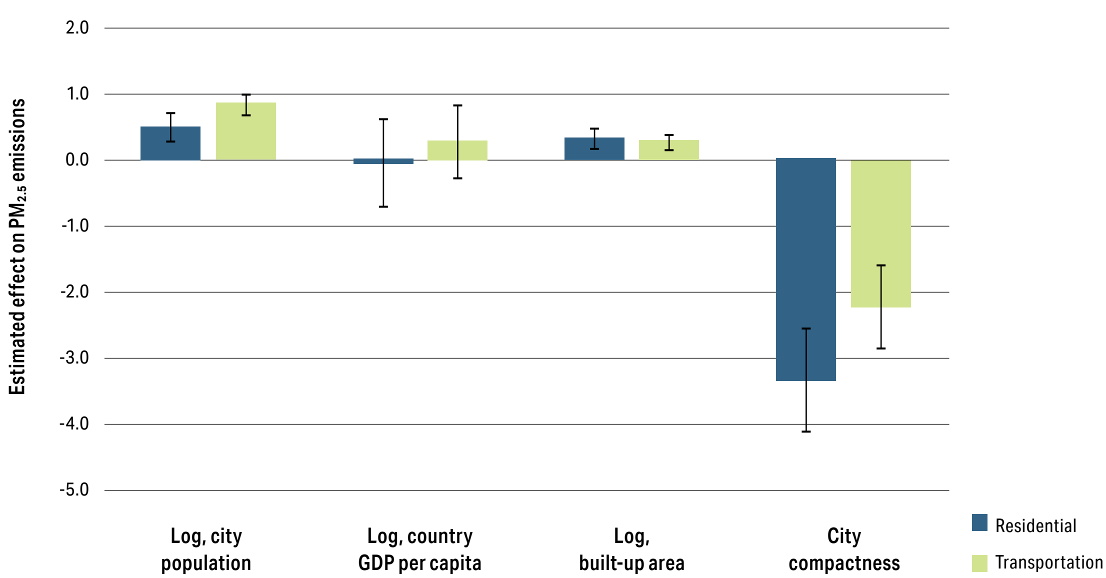
* For more on the Global Human Settlement Urban Centre Database R2019 see: https://human-settlement.emergency.copernicus.eu/ghs_stat_ucdb2015mt_r2019a.php

City governments are well placed to identify and address local sources of air pollution and vulnerabilities among local populations. While effective national air quality regulations are needed, city governments also have an important role to play in identifying and addressing sources of air pollution specific to their local context. These may include factors such as specific industrial activities, transportation corridors with heavy traffic, and landfills, as well as vulnerable local groups such as elderly residents, children, residents with underlying chronic health conditions, outdoor workers, and others.

Air pollution from construction sites includes dust from construction and demolition, smoke from on-site brick kilns, particles from on-site concrete mixing, and other sources. Particulate matter source apportionment studies suggest that construction is responsible for 6 percent of particulate matter emissions in Mumbai, India (CSIR–NEERI et al., 2018) and 8 percent of particulate matter concentrations in Xi'an in Northwestern China (Wang et al., 2021). In many low- and middle-income countries, regulations on reducing construction dust and other pollution either do not exist or are routinely ignored. Construction materials such as bricks and concrete are produced on-site in unsafe and unregulated ways, and construction workers often are not provided with any personal protective equipment (Safi, 2017). Beyond construction dust, $PM_{2.5}$ from diesel engines of construction machinery is also usually an important emissions source in cities, with practical mitigation options available.

Figure 2.9. Urban compactness reduces pollution

Determinants of $PM_{2.5}$ emissions for cities globally, residential and transportation sectors, 2015*



Source: Mukim and Roberts, 2023. Original World Bank figure based on data for 2,785 cities with a 2015 population of over 200,000 from the European Commission's Global Human Settlement Urban Centre Database R2019,** which derives its data on $PM_{2.5}$ emissions from the European Commission's Emissions Database for Global Atmospheric Research (EDGAR v5.0).

* For each sector, the graph presents estimated coefficients, together with the associated 95 percent confidence intervals, from a regression of a city's log $PM_{2.5}$ emissions on the log of its population; the log of the GDP per capita of the country in which the city is located, as well as its interaction with a dummy variable that takes the value 1 if the country is upper-middle- or high-income; the log of its built-up area; and a measure of the city's compactness (the Polsby-Popper Ratio). The regressions, which also control for a city's climate (precipitation, temperature, biome) and elevation, are based on cross-sectional data for 2015 with robust standard errors.

** For more on the Global Human Settlement Urban Centre Database R2019 see: https://human-settlement.emergency.copernicus.eu/ghs_stat_ucdb2015mt_r2019a.php

Cities can provide guidance on clean construction practices to reduce air pollution from construction. For example, measures may include enclosing construction sites, wetting surfaces, mechanical exhaust ventilation, providing personal protective equipment to workers, air quality monitoring, and other actions to track and reduce construction dust and its harmful impacts (Sheikh et al., 2020).

Cities can target outreach to groups that are particularly vulnerable to air pollution. Cities can identify vulnerable groups by using local air quality data, health data, and by mapping major sources of pollution. Vulnerable groups may include older residents, children, low-income women (who are disproportionately exposed to indoor air pollution), pregnant women, people with chronic health ailments, construction workers, street vendors, people living in informal settlements near major sources of pollution, and others. Cities can then work with these groups to reduce exposure to air pollution and ensure better access to medical care for issues related to air pollution.

Cities would benefit from developing an air quality emergency alert and response system. When $PM_{2.5}$ levels surpass thresholds at which vulnerable populations may experience health effects, cities need mechanisms to alert the public (particularly the vulnerable groups mentioned earlier) and provide clear guidance on how residents should protect themselves. They can also enact emergency measures to try to quickly reduce $PM_{2.5}$ levels. Such measures could include actions to reduce transport emissions (for instance, various restrictions on driving, imposition of high parking fees, cleaning of streets), industrial emissions (stopping power plants in or upwind of the city), stopping the open burning of waste (stopping crop burning and landfill fires, imposing heavy fines), and stopping construction dust (by halting all construction activities). Plans could also include measures to safeguard public health by closing schools, distributing masks, and others.

Box 2.7. Cities taking steps to improve urban air quality

Mexico City has managed to reduce air pollution through various means. Mexico City has reduced SO_2 levels by 91 percent, carbon monoxide by 90 percent, and PM_{10} by 60 percent since 1990. While reductions in $PM_{2.5}$ are more modest (reduction of 4 percent since 2004), the city claims that its air quality improvements measures have reduced premature deaths due to exposure to $PM_{2.5}$ by about 17,600 since 1990. Its efforts to improve air quality include the procurement of public buses that meet high emissions standards, the enforcement of vehicle emissions standards for private vehicles, investments in solid waste management, voluntary environment audits of businesses, the protection of natural areas, and other measures.

Tokyo is focusing on industrial fuels and diesel vehicles to improve air quality. For residents of Tokyo, the visibility of Mount Fuji, 100 kilometers away from the city, provides a natural benchmark for air quality. While 60 years ago it was only visible 20 days per years due to poor air quality, in 2014 it was visible for 138 days. This was due to decades of air quality improvement efforts from the Tokyo Metropolitan government, which include encouraging a shift in industrial fuel use away from SO_2-emitting heavy oil, enforcing strict emissions standards on diesel vehicles, and subsidizing the provision of PM-reducing devices for vehicles.

Beijing's massive urban afforestation program is having a significant impact on air quality. Beijing's urban afforestation program, the "Million Mu Project" (a mu is a unit of area equivalent to one 15th of a hectare), was launched in 2012. It resulted in more than 1,300 square kilometers of urban greening throughout the metropolitan area over the decade that followed. The program is estimated to have reduced the average population $PM_{2.5}$ exposure in the city by 4.2 percent over an eight-year period, which, in turn, is estimated to have reduced Beijing's annual healthcare cost by between US$32 and US$88 million (Xing et al., 2024).

2.8 RESILIENT LANDSCAPES

Landscape restoration in rural and urban settings can complement other air pollution reduction solutions—provided it is accompanied by efforts to manage forests in order to prevent wildfires as well as strategies to reduce deforestation due to the expansion of agriculture. Key interventions are relevant to all regions and include investing in adding trees and green cover to degraded landscapes to reduce sand and dust storms; diverting agriculture subsidies (which incentivize the expansion of the agricultural frontier) towards the promotion of agroforestry and silvo-pastoral systems that reduce soil erosion; financing urban forests that help to trap pollution; and implementing strategies to reduce the risk of wildfires.

Filtering polluted air is one of the numerous ecosystem services that trees and forest ecosystems provide. Landscape restoration plays an important part in reversing the effects of agriculture-induced deforestation, which causes air pollution (due to smoke linked to slash-and-burn agriculture) and sand and dust storms (due to lands being degraded and eroded). Planting trees and restoring degraded landscapes should be used as a complement rather than a replacement to other strategies to reduce air pollution. However, while some tree species could remove particulates, absorb harmful gases such as nitrogen dioxide and sulfur dioxide, and provide a microclimate effect (Kim et al., 2020) in urban settings, they can also be the cause of smoke and air pollution from wildfires if not properly managed.

Rural and urban landscape restoration has a clear role in addressing air pollution, despite limited quantification of its direct benefits. Local-level evidence confirms that effective landscape restoration and soil conservation, urban greening, and fire management collectively reduce ambient air pollution and mitigate climate impacts while enhancing resilience against future climate-induced shocks and providing biodiversity benefits, agricultural productivity improvements, and recreational value (Srivastava et al., 2023). Forest management interventions for cities and rural areas include preserving large native natural habitats within and around cities, sustaining healthy large-stature trees, planting trees in heavily populated or polluted areas, using long-living and low-maintenance trees, planting both leaf and coniferous trees where possible, and incorporating green spaces in city development plans.

Urban forest investments contribute to trap pollution. In addition to the example of Beijing (Box 2.8), economic assessments of Melbourne's urban forests show that about 1,000 trees remove 0.5 metric tons of air pollution per year at a dollar benefit of US$3,820 (City of Melbourne, 2012). United States cities spend between US$13 and US$65 annually per tree, with benefits ranging from US$31 to US$89 per tree (McPherson et al., 2005). Because public sector financing is insufficient, attracting private sector investment to fill the financing gap for many urban green infrastructure projects is key. Several financial instruments can be leveraged, including public-private partnerships, tax increment financing, loans, bonds, and carbon finance (Merk et al., 2012). Apart from long-term financing, urban forests need to be systematically and properly planted, maintained, and treated for diseases or pests by local authorities to avoid potential threats linked to trees. Each city is different in its approach to urban forest management.

Sand and dust storms, a major source of particular matter, are complex events stemming from both natural and anthropogenic activities that have devastating impacts on the environment, human health, agriculture, infrastructure, logistics, and transportation. Relevant national policies and institutional support can help to mitigate anthropogenic sand and dust storms. Some solutions include those related to sustainable land and water management, integrated landscape management, CCM and adaptation, urban shelterbelts (windbreaks), and better agricultural practices (Box 2.10). In some cases, especially when it comes to naturally generated sand and dust storms, it may be virtually impossible to prevent a dust storm. Apart from land restoration practices, monitoring, forecasting, and early warning, preventative measures should be applied to mitigate the multiple impacts of dust on human health.

Proper forest management practices play a key role in reducing the risk and severity of wildfires. Wildfires in Canada, driven by record-high temperatures and droughts, caused the northeastern United States to experience a yellow sky, smog, haze, and a red sun in early June 2023. New York City recorded $PM_{2.5}$ levels of 400 $\mu g/m^3$, 11 times the US Environmental Protection Agency's 24-hour standard. This made New York the most polluted major city globally that day. Climate change and El Niño-Southern Oscillation effects have intensified wildfire seasons, increasing the burned area in the United States from 1.3 million acres in 1983 to more than 7.6 million acres in 2020. This trend extends globally, with extreme wildfires affecting regions like the Amazon, Alaska, Australia, California, Europe, Indonesia, Russia, and Türkiye, contributing to widespread pollution and desertification (Srivastava et al., 2023).

Box 2.8. How innovation in urban forestry in Korea enhances air quality for city dwellers

Innovative approaches like the Republic of Korea's Urban Wind Ventilation Forest Project further demonstrate the potential of urban forestry to improve environmental outcomes. By utilizing the cooling effects of cold air, these projects create green corridors that enhance air quality, reduce urban heat islands, and improve living conditions. Initially implemented in cities like Seoul and Busan, this concept has now expanded to 17 cities across Korea, showcasing a scalable model for urban greening with significant environmental (decreased $PM_{2.5}$ and other pollutants) and social benefits (World Bank, 2023d).

Box 2.9.
Drawing on nature to reduce air pollution from dust storms

Dust storms contribute significantly to air pollution in the Middle East and North Africa, losing the region about US$13 billion in GDP every year (World Bank, 2019). In Sub-Saharan Africa, desert dust is the largest source of air pollution, with substantial transboundary effects reaching beyond the region itself.

In recent decades, various ambitious initiatives—including several supported by the World Bank—have sought to reduce dust pollution by rolling out sustainable land-management practices and combating land degradation and desertification. These initiatives include:

- The Sahel RESILAND Program, which is restoring native plant life to landscapes across the Sahel-Sahara region
- The Sustainable Land and Water Management Project in Northern Ghana
- The Africa Union's Great Green Wall initiative[i]
- The Resilient Landscape Program, which contributes to reducing sand and dust storms in Central Asia by planting trees and shrubs to fix the soil.

i For more information on the African-led Great Green Wall Initiative, visit https://www.unccd.int/our-work/ggwi

Wildfires can be caused by various factors, including human activity—which causes between 85 percent and 90 percent of such occurrences—and natural events. Effective forest management practices are essential for reducing their risk. These practices include: (i) large-scale forest conservation and restoration; (ii) fuel reduction; (iii) creating defensible spaces by clearing flammable vegetation and creating buffer zones around homes and infrastructure; (iv) controlling and reducing the spread of non-native invasive species including weeds that alter fuel regimes; (v) increasing habitat connectivity to facilitate recovery through revegetation and repopulation; and (vi) prediction and real-time monitoring of forest health and early detection of wildfire risks. Other preventive measures can include: (i) monitoring of land uses that increase fire risk or threaten fire resilience; (ii) collaboration and engagement with local communities, landowners, and stakeholders to improve overall forest management practices and enhance wildfire prevention efforts; (iii) building fuel breaks to manage fire size, (iv) raising awareness and education. Forest management can also reduce threats from naturally occurring wildfires. Practices such as postfire seeding to reduce soil erosion and promote new growth and reforestation, controlling invasive species, and planting native species are crucial in helping reduce harm from wildfires.

Box 2.10.
Indonesia's forest fires: Raising awareness by analyzing the cost

Indonesia experiences devastating wildfires. In 2023, wildfire affected a million hectares. Before that, in 2019, Indonesia experienced devastating wildfires that impacted about 1.6 million hectares, creating a smoky haze that worsened air quality in neighboring countries. The 2019 fires released nearly 604 million tons of carbon dioxide into the air, were associated with respiratory health complaints from about 900,000 individuals, and cost the country US$5.2 billion in economic losses (0.5 percent of GDP).

For Indonesia, fire prevention is crucial in its endeavor to reduce greenhouse gas emissions and enhance air quality. The government has committed to restore 2.49 million hectares of degraded peatland, a project estimated to cost between US$3.2 billion and US$7 billion (Kiely et al., 2021). Strengthened measures for forest and peat conservation—including reduced clearing, the implementation of zero-fire policies prohibiting fire-based land clearing, peatland rewetting, and fire controls—have contributed to a slowdown in land-related emissions (World Bank, 2023b).

The World Bank is also involved in projects to improve forest and land fire prevention and suppression in targeted project areas in Indonesia, such as the Sustainable Landscapes Management Program.[i] This program brings cross-sectoral expertise to support an integrated approach, including support for integrated fire management and improved incentives to conserve and manage forest resources.

i For more information on the Sustainable Landscapes Management Program, see https://www.worldbank.org/en/programs/indonesia-sustainable-landscapes-management-program

The following policy measures would maximize the air quality benefits created by investing in trees and restoring landscapes:

- **Address institutional and policy barriers.** Integrate landscape restoration and urban forests into national adaptation plans. Introduce rotational grazing or grazing bans in severely degraded areas and shift harmful agricultural subsidies to incentives for restoration.

- **Promote the adoption of appropriate technologies.** Enhance extension services for integrated landscape restoration and urban forest management. Establish support mechanisms for initial investment costs.

- **Mobilize finance.** Include urban forestry and landscape restoration in a country's green taxonomy. Optimize public spending via public expenditure reviews, adopt a multisectoral budget approach, and convene multi-donor platforms for large-scale resource mobilization.

Other potential priority actions to restore landscapes include the following:

- **Restore degraded land surrounding urban areas** using local technologies such as natural regeneration, which are cost-effective and beneficial for climate adaptation

- **Provide training to farmers on landscape restoration techniques** to enhance land productivity and minimize soil erosion

- **Shift subsidies away from harmful agricultural practices** that drive deforestation and towards agroforestry and silvo-pastoral systems

- **Invest in urban forests**

- **Implement integrated fire management practices**, including adopting the 5R approach to wildfire management (review, reduce risks, readiness, response, and recovery).

Box 2.11. Innovative productive landscape restoration strategies in Central Asia

Programs such as the World Bank's Central Asia RESILAND Program play a vital role in mitigating soil dust pollution and underscoring the critical need for land restoration to minimize environmental and human impacts (Agostini and Proskuryakova, 2022).

Under the RESILAND Central Asia initiative, the World Bank collaborates with governments and local communities to achieve land restoration goals that promote sustainable ecosystem management, empower communities, and improve food security. Achieving these objectives requires Central Asian authorities and stakeholders to shift their focus from conservation-only approaches to innovative productive landscape restoration strategies that not only combat land degradation but also generate income and economic opportunities.

2.9 ADAPTIVE STRATEGIES TO REDUCE THE IMPACTS OF AIR POLLUTION

The health and education sectors provide adaptive strategies to reduce the impacts of air pollution on vulnerable populations and support behavioral-change efforts needed to reduce air emissions.

The health sector sits at the frontline of the consequences of air pollution and plays a key role in identifying and managing adverse human health outcomes. Through effective secondary prevention and treatment, it can mitigate the impacts of poor air quality on childhood development and facilitate the reintegration of individuals into economically productive employment after air-pollution-related illnesses. The health sector can support other sectors in primary prevention efforts by providing data and information on the health impacts of air pollution and engaging in communication and advocacy efforts aimed at improving air quality.

Strategies to reduce health risks from air pollution should ideally be tailored to local conditions, especially the national income classification level. Health systems in LMICs are typically less robust and require more comprehensive interventions across all levels of the health system.

The health sector plays a crucial role in highlighting the scope and specifics of health impacts caused by air-pollution-related diseases. The health sector can provide data on morbidity and mortality related to air pollution, thereby reinforcing arguments in collaboration with other governmental sectors. Routine integrated surveillance systems for air-pollution-related disease facilitate building evidence and awareness for health and air pollution policy interventions. It is important that these systems are set up to be integrated with hydrometeorological services. This enables anticipating poor air quality in the short term, as well as predicting longer-term trends induced by climate change. Routine integrated surveillance systems also need to be set up to inform early warning systems that feed information to local authorities to generate public health messaging during air pollution peaks, and to health responders to ensure vulnerable individuals are appropriately identified.

A key way in which the health sector can address the health impacts of air pollution includes subsidies for cost-effective secondary prevention measures—such as respiratory face masks and air purifiers—and targeting these to the most vulnerable populations. For example, in India, the use of respiratory face masks during times of poor air quality could potentially decrease short-term excess mortality by 13 percent and reduce associated costs if at least 30 percent of Delhi residents adhere to alerts from the Air Quality Early Warning System issued by the Ministry of Earth Sciences (Jat et al., 2024). Governments can provide subsidies for face masks and air purifiers to economically disadvantaged groups or those with co-morbidities. In Bangladesh, the government has significantly reduced import taxes on air purifiers to make them more affordable. The Bangladeshi government also plans to distribute face masks to informal-settlement dwellers. In India, social health insurance covers the cost of hospitalization for diseases related to air pollution. Measures that prioritize equitable secondary prevention are also important in high-income countries. For instance, in the United States, Medicaid provides subsidies for air filters to support the most vulnerable populations. However, these secondary prevention measures should be regarded as critical actions that coincide with the implementation of long-term air pollution reduction strategies.

In both high- and low-income countries, community health workers (CHWs) and the primary health care system play a crucial role in awareness-raising and promoting public adherence to cost-effective prevention measures. In India, CHWs raise awareness about air pollution and encourage the use of face masks. Mobile clinics also engage in outreach activities with community outpatient departments to respond to anticipated increases in demand during periods of poor air quality. In some countries, various levels of government conduct public awareness campaigns at both national and decentralized levels.

It is important that health-system capacities are sufficiently strengthened and financed to respond to increased demand during periods of poor air quality. This includes ensuring emergency care departments and ambulances have the necessary equipment and medicines available to manage increased respiratory and cardiovascular emergencies, as well as ensuring sufficient trained staff to manage air pollution-related diseases.

The education sector is vital to raise awareness among the current generation and to equip future generations with the skills and knowledge to address air pollution. Important concepts such as clean cooking and heating, designing and implementing clean-air strategies, and reducing emissions can be embedded into school curricula, which would coincide with building teachers' capacity on these topics. The sector can also raise awareness and spark behavioral change on topics such as the clean cooking and heating agenda by engaging communities through schools, empowering educators as advocates to lead community-awareness efforts, and promoting student-led initiatives.

2.10 AIR QUALITY MEASURES AND CLIMATE CHANGE MITIGATION INTERACTIONS

Despite a significant overlap between climate-change mitigation measures and policies to reduce air pollution, not all efforts to mitigate climate change by reducing greenhouse gas emissions lead to improved air quality. Therefore, to maximize the synergy between efforts to mitigate climate change and those to manage air quality, these strategies should account for the impacts their measures and policies—including fiscal policies such as carbon taxes—have on each other's goals: to reduce greenhouse gas emissions and reduce air pollutant emissions, respectively.

Considering the implications that policies and measures have on both AQM and CCM can maximize synergies and more efficiently manage cases when divergent impacts are identified, so supporting policy development across sectors, including fiscal policy. Fiscal policy is commonly used by governments to incentivize emission reductions across sectors. However, fiscal policies that target one of the issues (AQM or CCM) without considering the impact on the other might fail to identify possible divergent impacts. For instance, introduction of a sulfur tax discourages the use of coal which is beneficial for both AQM and CCM. However, introducing a carbon tax or eliminating fossil fuel subsidies to reduce GHG emissions might push households to burn more unsustainably sourced biomass or even waste, which is detrimental to local air quality. As such, the introduction of a carbon tax should be accompanied by incentives to use cleaner fuels fit for the local context.

To maximize AQM and CCM synergies, it is essential that the air quality impacts of policies and measures included in CCM strategies are fully accounted for. In addition to its interaction with CCM policies and measures, AQM actions could have an impact on climate change adaptation.[22] Many of the measures for both climate change adaptation and AQM need to be implemented at the local level, which highlights the need to recognize their interconnectedness and ensure that AQM at this level also considers the adaptation effects of its policies and measures.

Examples of synergies between AQM and climate change adaptation include:

- Black carbon is both an air pollutant constituting a major part of $PM_{2.5}$, as well as a short-lived climate pollutant. Black-carbon deposition on snow and ice surfaces accelerates melting, and reducing its emissions would not only improve air quality but also slow down glacier and sea ice

22 Climate change adaptation refers to actions that help reduce vulnerability to the current or expected impacts of climate change.

melting, which is crucial to maintain regional water supplies and sea levels.

- Black carbon ground-deposition can alter soil properties and reduce productivity on agricultural lands. It can affect natural ecosystem health by altering soil-nutrient dynamics and vegetation composition. Thus, along with enhancing the resilience of agricultural systems to droughts and extreme weather events, reducing black carbon emissions would also help protect natural ecosystems and preserve the services they provide.
- Developing green infrastructure such as urban forests, green belts and green roofs helps mitigate climate change by absorbing CO_2 and reducing the urban heat island effect. At the same time, green infrastructure can improve air quality by filtering pollutants and blocking the transport of air pollutants to cities.
- Air-quality and meteorology-monitoring networks and models can be upgraded to forecast air pollution episodes and warn about extreme weather events related to climate change that could have an impact on air quality, such as heatwaves and wildfires. Such warning systems could help minimize the impact of air pollution and climate-change related events on vulnerable groups.

Table 2.1 outlines examples of emission reduction policies and measures that have synergetic and divergent impacts on AQM and CC, respectively. It also provides tradeoffs to consider in optimizing the outcomes for both AQM and CCM.

Addressing air quality challenges requires substantial and

Table 2.1.
Interactions between air quality management and climate change mitigation for policies and measures in key sectors

Sector	Measures with synergetic impacts	Measures with divergent impacts	Considerations for optimized integrated policies and measures
Power generation and industry	• Energy efficiency measures and optimized combustion processes that reduce fuel consumption. • Using renewable energy sources and/or electricity generated from renewable energy sources to replace fossil fuels.	• Installing post-combustion emissions control equipment at fossil fuel-fired facilities reduces air pollutants but could prolong the use of the facility. • Emissions control equipment uses additional energy, which increases fuel use. This leads to an increase in GHG emissions if fossil fuels are used.	• Incentives for implementing energy efficiency measures and switching to cleaner (preferably renewable) energy sources and cleaner production processes would enhance synergies between air quality management (AQM) and climate change mitigation (CCM).
Residential energy use	• Decreased use of coal for heating and cooking. • Energy efficiency measures. • Switching from non-sustainable biomass to liquefied petroleum gas (LPG) or natural gas for cooking and heating. • Switching from fossil fuels to non-biomass renewable energy sources.	• Reducing residential use of biomass reduces air pollution, but replacing sustainably sourced biomass with natural gas or LPG could lead to increased GHG emissions. • Replacing solid fuels with electric energy generated using fossil fuels could also lead to an increase in GHG emissions	• Incentives for the use of non-biomass renewable energy sources at household level could be provided. • If electricity is mainly generated by renewable energy sources and if the energy system has sufficient capacity, then switching to electric energy can be beneficial for both AQM and CCM. • However, in many areas without reliable access to electricity, use of LPG might be considered in the short term with the goal of transitioning to non-biomass renewable energy sources. • If biomass is still a major source of household energy, then additional measures such as fuel and appliance performance standards are needed to reduce the impact on air quality.
Transport	• Switching to electric vehicles (provided electricity is generated from low-emission, renewable energy sources). • Promoting public transport and non-motorized, sustainable urban mobility. • Traffic-demand management measures. • Fuel and vehicle standards.	• Diesel vehicles are more CO_2-efficient but emit more air pollutants compared to gasoline vehicles. • Catalytic converters reduce emissions of air pollutants but increase fuel use, which in turn leads to increased GHG emissions.	• The CCM benefits and the air quality impacts of different types of vehicles may be thoroughly assessed before designing policies and measures. • Implementing additional measures to reduce demand for vehicle use will benefit both AQM and CCM (for instance, incentivize non-motorized modes of transport, traffic-demand management, congestion fees, low emission zones, and so on).

Sector	Measures with synergetic impacts	Measures with divergent impacts	Considerations for optimized integrated policies and measures
Agriculture	• Improving animal diets and manure management. • Improving nitrogen management at farm level. • Low-emission application of manure and inorganic fertilizers to soils. • Eliminating open-field and crop-residue burning	• Certain manure management practices (for example, composting manure) can increase volatile organic compound and ammonia emissions. • Covered manure storage might reduce ammonia emissions but increases methane emissions.	• Finding the optimal balance between AQM and CCM requires a context-specific approach, as integrated strategies depend on climate, soils, manure type, and agricultural management practices. • Incentives for upscaling crop residues and biogas production may be provided to maximize AQM and CCM benefits.
Forestry and greening	• Establishing green belts around cities considering the dominant wind directions. • Developing and maintaining urban green areas. • Wildfire risk reduction and prevention measures.	• Forestry and greening measures largely have synergetic impacts for AQM and CCM.	• Unlike measures in most other sectors, greening measures enjoy widespread stakeholder acceptance. In addition to the AQM and CCM co-benefits, greening measures have other benefits such as urban temperature control and quality improvement of the living environment, whereas wildfire risk reduction and prevention measures preserve ecosystems and secure the safety of the population and key infrastructure.
Waste management	• Eliminating open waste burning. • Implementing measures to achieve higher tiers of waste management (for example, reducing or eliminating landfilling, recycling, waste prevention).	• Depending on the waste management system, recycling might increase GHG emissions if additional fossil fuels are consumed in the collection, transportation, sorting, and processing of waste to be recycled.	• There is large potential for achieving AQM and CCM benefits in the waste management sector. Therefore, incentives to move up the waste management hierarchy generally present "win-win" opportunities for AQM and CCM.

Source: World Bank.

3 FINANCING FOR ACCELERATED ACCESS TO CLEAN AIR

sustained investment, but the current financing landscape for air quality management remains fragmented and underdeveloped with significant gaps between available funding and actual needs.

Estimates indicate that the scale of financing required exceeds existing resources, underscoring an urgent need to mobilize new capital sources. Unlocking these investments requires a multifold approach that includes: (i) establishing fiscal and regulatory levers, such as tax incentives and structured mandates, to create market readiness for air quality investments; (ii) deploying targeted de-risking mechanisms, including credit guarantees and viability gap funding, to lower investment barriers and attract private sector participation; and (iii) scaling investments through sector-specific financial instruments. This chapter outlines sustainable and scalable pathways to meet the extensive financing needs for AQM globally by aligning financing strategies with policy reforms, integrating with climate policies, and creating enabling environments.

MAIN MESSAGES IN THIS SECTION

- Ample evidence shows that the benefits of addressing air pollution outweigh the costs, and that the costs of achieving the Clean Air Targets (as defined in Box 1.2) through integrated policies are affordable.
- The current financial landscape faces challenges including sectoral imbalances, the financing of initiatives that indirectly subsidize air pollution, and a lack of business incentives for private financing.
- Integrating air quality management and climate change mitigation measures is expected to attract more funding and maximize the impact of these measures. Attracting the private sector through innovative mechanisms is essential, as is providing an enabling environment for financial reforms.
- Financing instruments should be tailored to the context of the region, and may include blended finance, results- and performance-based financing, guarantees, outcome bonds, and revolving funds.

3.1 THE CASE FOR AIR QUALITY FINANCING

Ample evidence shows that the benefits of reducing air pollution far outweigh the costs.

The economic rationale for air quality investments is strong. It is estimated that global economic costs from ambient air pollution total approximately US$6 trillion per year, equivalent to 4.6 percent of global GDP in 2020, with some regions seeing higher percentage losses of their GDP due to pollution-related health and economic impacts. There is a strong argument for investing in AQM—in the US, every US$1 spent on air pollution control yields an estimated US$30 in economic benefits (USEPA, 2011), and for countries facing high exposure to air pollution, like China and India, air quality interventions also yield substantial health and economic benefits. In China, a significant reduction in $PM_{2.5}$ and PM_{10} concentrations resulted in 47,240 fewer premature deaths in 2017 compared to 2013 (Huang et al., 2018), while in India's Delhi National Capital Region, the cost-benefit ratio of pollution abatement measures shows positive returns, with benefits exceeding costs by 2 to 3.6 times (The Energy and Resources Institute, 2021), reinforcing the economic rationale for addressing air pollution.

Although significant additional financing is required, achieving air quality targets appears affordable. Achieving the Clean Air Targets defined in Box 1.2 by 2040 through Integrated Policies—combining AQM with climate actions—is expected to require additional cumulative investments of approximately US$3.2 trillion globally. Projections suggest that the additional global investment in AQM will need to rise from US$8.5 billion in 2020 to US$13.9 billion by 2040. However, while substantial, these investments appear manageable when considering their expected decline over the period in terms of GDP, falling from 0.95 percent of global GDP in 2020 to only 0.49 percent by 2040.

Meeting the financing gap calls for a shift from viewing air quality investments as solely driven by public policy and regulation to seeing them as market opportunities for private sector engagement. Addressing market failures by complementing well-designed regulations with pollution pricing, repurposing subsidies, and creating enabling environments for cleaner technology deployment can help mobilize both public and private capital for air quality improvements. Strategic financing approaches that prioritize easily implementable actions—such as targeting pollution sources with established revenue streams or clear cost-saving potential—can act as catalysts.

3.2 THE CURRENT FINANCING LANDSCAPE

The air quality financing landscape is currently inadequate to address the air quality crisis.

While suitable for covering recurring costs such as staffing and environmental monitoring and enforcement, government budgets are insufficient and not appropriate for the scale of investment needed to address the global air quality crisis. In the EU, where member states collectively allocated US$15.6 billion to pollution abatement in 2021, air quality receives a smaller proportion of environmental budgets compared to sectors like wastewater and waste management because most air quality improvement measures are privately financed by regulated industries and other economic actors (CPI, 2023).[23] The funding gap in both public and private financing is particularly pronounced in low-income countries, where fiscal constraints and underdeveloped capital markets severely limit the capacity to scale up investments in air quality. To bridge this gap, governments need to balance public funding with incentivizing private investment to effectively expand air quality initiatives. Financing involves structured mechanisms like loans, guarantees, and equity investments to enable large-scale infrastructure projects such as transport electrification. Sustained public-sector funding will be crucial for financing policy development and for staffing AQM agencies to ensure effective monitoring and enforcement.

Development finance institutions (DFIs) and other international development funders only cover a small fraction of global air quality financing needs. While different methodologies for classifying air quality funding are possible, analysis from the Clean Air Fund suggests that international development funders, including bilateral and multilateral DFIs and governments that provide international funding, allocated US$112 billion to air quality-related projects between 2018 and 2022. This represents only 5.9 percent of total international development funding of US$1.89 trillion during the same period. Multilateral DFIs provided the majority of DFI contributions to air quality, accounting for 63 percent of total DFI air quality funding (CPI, 2024).

Regional and sectoral imbalances further complicate the financing challenge. Regional analysis by the Clean Air Fund shows a significant concentration of DFI funding in Asia, while other regions, particularly Africa and low-income nations, receive comparatively less support. This geographical imbalance highlights the need for more balanced funding distribution. Sectoral imbalances also persist, with 61 percent of funding for air quality directed towards transport, while other critical sectors remain underfunded (CPI, 2024). This uneven distribution underscores the need for a more balanced and diversified funding strategy.

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23 The Clean Air Fund's analysis uses a specific methodology to classify air quality-related projects, focusing on direct interventions and co-benefits. Different classification approaches might yield varying estimates of air quality funding allocation. The numbers presented should be considered indicative of broad funding patterns rather than definitive measurements. There are no standardised reporting mechanisms around air quality funding, which makes it harder to fully account or identify all funding that goes to air quality.

Market-based reforms, including pollution pricing and subsidy rationalization, show promise for sustainable air quality funding. These reforms should be designed to capture both climate and air quality benefits through integrated policy frameworks. In 2024, Nepal introduced South Asia's first green tax on fossil fuels at US$1.5 per ton of carbon, projected to raise revenue by 0.7 percent and cut GHG emissions by 0.9 percent annually. In China, the Innovative Financing for Air Pollution Control Program has supported efforts to mitigate climate change by reducing CO_2 emissions. This program uses the Program for Results (PforR) modality to mainstream green financing in financial institutions, supporting commercial banks to provide financing for enterprises to reduce air pollutants and carbon emissions.[24] Additionally, China launched its carbon emissions trading system in 2021, which has become the world's largest carbon market, aiming to synergistically reduce both CO_2 emissions and air pollutants (Chen et al., 2022). Ensuring that air quality impacts are systematically integrated into emissions trading system design can enhance its effectiveness for pollution reduction. Vietnam has introduced a domestic carbon emissions trading scheme through its revised Law on Environmental Protection, which aims to create a market instrument where production facilities, localities, and countries can buy credits to offset their GHG emissions, based on the "polluter pays" principle (World Bank, 2021b). To fully leverage air quality benefits, such schemes should incorporate targeted mechanisms—such as emission reduction credits for fine particulate matter ($PM_{2.5}$) and other local pollutants—into their framework.

There is a growing shift from standalone environmental projects to integrated programs that combine air quality improvements with climate objectives. The World Bank's air quality financing has evolved from targeted projects, such as the earlier Bangladesh vehicle emissions control project, to large-scale, policy-driven interventions such as China's Hebei Air Pollution Prevention and Control Program, which combines policy reforms with comprehensive investments, using results-based financing to strengthen institutions and address pollution systemically. This shift reflects the recognition that sustainable air quality improvements require addressing market failures and enhancing institutional capacity, not just funding direct interventions.

DFIs are increasingly deploying non-traditional financial instruments to attract private sector investment including guarantees, risk-mitigation tools, and bespoke financing mechanisms such as sustainability-linked loans, green bonds, development policy financing, result-based financing, blended finance approaches, and air quality impact bonds. Although promising, these tools remain underutilized in the air quality sector, signaling an opportunity for scaling up their use. This environment also presents a chance to broaden grant and concessional financing and encourage private sector engagement through structured financial tools. Appendix C provides examples of DFI interventions across financial modalities.

Private sector involvement in air quality financing remains limited, particularly in direct investments. While public funds are essential for staffing, assessments, and enforcement, large-scale technology investments need private sector capital. Private sector reluctance stems from uncertain

24 More information about the Innovative Financing for Air Pollution Control in Jing-Jin-Ji Program is available at: https://www.worldbank.org/en/results/2020/06/21/china-fighting-air-pollution-and-climate-change-through-clean-energy-financing

returns, fragmented pollution sources, and complex revenue models. However, there are promising cases where policy reforms and structured revenue models have drawn private interest, such as China's Jing-Jin-Ji Program and Green Finance pilot zones (Xu et al., 2023). Such initiatives demonstrate that addressing market failures through pollution pricing, revenue guarantees, and risk-sharing mechanisms can make air quality projects more attractive to private investors.

3.3 MOBILIZING SUSTAINABLE FINANCING FOR AIR QUALITY

Achieving lasting improvements in air quality requires a strategic approach to financing that combines policy alignment, tailored financial tools, and private sector engagement.

Leveraging blended finance models, such as combining concessional public funds with private capital, can help mobilize resources at scale by de-risking investments and attracting private sector participation. This section outlines essential components: integrating AQM with climate action to unlock larger funding pools; creating supportive environments through policy reforms and robust institutions; and employing customized financial mechanisms that address specific pollution sources to attract private investment and manage risks. Together, these elements create a comprehensive strategy to mobilize the resources needed for effective air quality management across various sectors and regions.

3.3.1 INTEGRATED CLIMATE AND AIR QUALITY POLICIES FOR ENHANCED IMPACT

Integrating air quality with climate policies can attract more financing and maximize impact. Aligning air quality actions with Nationally Determined Contributions (NDCs) under the Paris Agreement and using international frameworks like the Geneva Convention on Long-range Transboundary Air Pollution can facilitate cross-border cooperation and coordinated actions to reduce emissions across borders, enhancing the effectiveness of national air quality policies, as seen in Australia's National Health and Climate Strategy,[25] which links emission reduction with public health. This is also captured in the WHO's Sourcebook on Integrating Health in Urban and Territorial Planning (UN-Habitat and WHO, 2020).

Integrated policies lead to substantial savings. Integrating climate and air quality management measures to achieve the Clean Air Targets defined in Box 1.2 reduces investment needs by 40 percent compared to standalone air quality measures, primarily by reducing fossil fuel consumption and

25 Australia's National Health and Climate Strategy is available at https://www.health.gov.au/sites/default/files/2023-12/national-health-and-climate-strategy.pdf

Box 3.1. Assessing integrated air quality management and climate change mitigation policies in Kazakhstan

A World Bank report on the interactions between air quality management (AQM) and climate change mitigation (CCM) in Kazakhstan suggested that cost-effective optimal strategies to separately address air pollution and CCM could differ (Zlatev et al., 2021).

In Kazakhstan, as in many other countries, priority measures to improve air quality in cities target small residential stoves and boilers that use coal for heating and cooking, while priority measures for CCM involve large point combustion sources that burn coal in the power sector and industry.

A follow-up city-level report considered the design of an optimal AQM, an optimal CCM, and an integrated AQM and CCM strategy for Almaty and Astana (Zlatev et al., 2022). The report concluded that it was possible to design cost-effective optimal integrated interventions—especially when reducing the use of coal is a priority for both AQM and CCM.

To assess the costs of improving air quality and reducing greenhouse gas emissions, several scenarios until 2030 were considered in the modeling for each city. The modeled scenarios included a business-as-usual scenario and scenarios achieving an air quality target, or a greenhouse gas reduction target, or both. Table 3.1 summarizes the system costs, from a social planner's perspective, of implementing the different scenarios in Almaty.[i] The system costs of the AQM scenario are the lowest—€58 million per year lower than the business-as-usual scenario, €10 million per year lower than the CCM scenario, and €15 million per year lower than the integrated scenario. Costs in all scenarios are lower than the business-as-usual scenario, further highlighting the need to take action to address AQM and CCM.

Table 3.1.
System costs of achieving the air quality and greenhouse gas targets for the different modeled scenarios in Almaty

Scenario	Estimated system costs* (€ million/year) for Almaty
Business as usual	1,713
AQM (achieving $PM_{2.5}$ exposure below 25 μg/m^3, but not the GHG reduction target)	1,655
CCM (achieving 25 percent CO_2 reduction, but not the $PM_{2.5}$ exposure target)	1,665
Integrated AQM and CCM (achieving both $PM_{2.5}$ exposure and greenhouse gas reduction targets)	1,670

* System costs considered in this study include annualized investments, operating costs, and fuel costs in the power and heat sector, buildings, heating systems, and road transport.

Source: World Bank.

The study acknowledged that there is a cost difference between what is economically efficient for society from the social planner's perspective and what is financially attractive to individuals and private actors in current market conditions, creating an incentive gap for implementing the AQM and CCM scenarios. An option to close the incentive gawp would be to use fiscal instruments to internalize the externalities of air pollutants and/or greenhouse gas emissions. The study suggested that a carbon tax of €18 per ton of CO_2 in Almaty would reduce total upfront subsidies needed to implement an integrated AQM and CCM strategy by 19 percent, while also yielding annual revenues of about €112 million per year. However, the impact of a carbon tax on air quality should be carefully considered, and additional regulation and incentives might be needed to prevent households from burning biomass or waste as a response to the carbon tax, which would lead to air pollution. Nevertheless, designing adequate incentives, including fiscal, is integral to support integrated AQM and CCM strategies.

i The social planner's perspective aims to minimize societal resources while improving air quality and reducing greenhouse gas emissions. As such, measures appear to be cost-effective if net costs are accounted for over the full technical lifetime of the measure, where upfront investments can be (partially) compensated for by subsequent savings in operating costs.

avoiding costly end-of-pipe solutions. An integrated policy pathway is estimated to lower global GDP expenditure on air quality from 0.95 percent in 2020 to 0.45 percent by 2040, compared to 0.6 percent under using solely AQM measures. Under the integrated approach, total additional investments for air quality improvements in 12 regions[26] are estimated at US$3.2 trillion by 2040, 30 percent less than under separate stated policies. While the total cumulative investment need of US$3.2 trillion

includes both climate and air quality measures, attempting to separate these costs would understate the synergies of integration as many interventions simultaneously deliver both climate and air quality benefits, making their costs inherently integrated.

Financial incentives are essential in sectors with limited capital. While integrated policies reduce overall investment costs, sector-specific investments remain critical for achieving air quality targets, underscoring the importance of a tailored financing approach that directs resources where they are most needed while leveraging the cross-sector benefits of combined air quality and climate interventions. For example, improving access to finance for black carbon mitigation projects will deliver both air quality and climate goals. Subsidies, tax incentives, and fiscal tools will be required to support sectors and households facing high upfront costs for cleaner technologies, as demonstrated by Kazakhstan's financing model (Box 3.1) (Zlatev et al., 2021).

3.3.2 ENABLING ENVIRONMENTS AND POLICY REFORMS

Reforms are essential to mobilize sufficient capital for air quality initiatives. Fiscal discipline plays a critical role in financing, and foundational elements like the "polluter pays" principle, the pricing of externalities, and targeted prior actions are crucial for sustainable financing. Strong fiscal discipline

26 The financing options developed here exclude the three regions where stated policies will largely eliminate $PM_{2.5}$ exposure. The remaining 12 regions cover 93 percent of the global population.

and clear links to health outcomes strengthen the economic case for air quality investments across all pollution sources. While revenue streams vary by sector, the combination of fiscal sustainability and quantified health benefits creates a stronger foundation for long-term financing. Embedding air quality goals within the NDCs under the Paris Agreement, as Chile did by integrating black carbon reduction within its NDCs, allows countries to leverage international climate finance.

Public support remains essential, especially for non-revenue-generating projects like reducing pollution from households and small-scale industries. Decentralized pollution sources that lack strong revenue streams require public funding to attract private co-investment. Mature technologies, such as energy-efficient heating, can use conventional financing, while emerging technologies need guarantees or venture capital due to higher risks. The World Bank's Pilot Auction Facility, for example, uses floor price guarantees and results-based payments to stimulate private investment in methane reduction.[27]

27 More information about the Public Auction Facility is available at https://www.pilotauctionfacility.org/content/about-paf

Box 3.2. Leveraging priority sector lending in India

India's priority sector lending framework, mandated by the Reserve Bank of India, requires commercial banks to allocate a portion of their lending portfolios to sectors that contribute to inclusive economic growth.

Traditionally covering agriculture, micro-, small-, and medium-sized enterprises as well as affordable housing, priority sector lending was expanded to include renewable energy and clean technologies, demonstrating its potential as a financial tool for addressing environmental challenges.

Under priority sector lending, bank credit is directed toward renewable energy, biogas, and energy efficiency projects, enabling these sectors to access financing at competitive rates with extended tenors. This has helped accelerate India's energy transition, reducing reliance on coal and biomass combustion, which in turn has delivered significant air quality benefits by lowering $PM_{2.5}$ emissions.

Additionally, including renewable energy in the Harmonized Master List of Infrastructure has enhanced access to long-term financing by raising borrowing limits and improving capital flow. This framework has lowered financing costs for solar, wind, and bioenergy projects, supporting decarbonization while substantially reducing air pollution from fossil fuel-based power generation.

This experience highlights how priority sector lending can unlock commercial bank lending for environmental priorities, offering a model for expanding financial flows into air quality management.

Private sector engagement requires clear regulation and de-risking mechanisms. A stable regulatory environment with clear emissions standards and pollution pricing encourages cleaner technologies. De-risking tools like guarantees, concessional loans, and blended finance lower private investor risks. Policy reforms in Peru, Chile, and Mexico City demonstrate how regulatory adjustments paired with sustainable transportation policies attract investment in air quality. China's Hebei Air Pollution Prevention and Control Program serves as an example of how combining policy reforms with results-based financing can effectively mobilize resources at scale for air quality improvements while strengthening institutional capacity (Choi and Li, 2021).[28]

Priority sector lending (PSL) can be a powerful tool to direct commercial financing toward air quality investments. PSL has successfully channeled credit to key development areas, including renewable energy in India (Box 3.2) by mandating banks to allocate a portion of their lending portfolios to priority sectors. Expanding this approach to air quality investments—particularly for industrial pollution control, clean technology adoption, and municipal AQM—can enhance financial flows while ensuring long-term sustainability. The World Bank's Global Challenges framework, which prioritizes energy access, climate change management and adaptation, and environmental sustainability, aligns closely with PSL's objectives. When structured effectively, PSL policies can lower financing costs, improve access to long-term capital, and create stable investment environments for air quality solutions. For maximum impact, such policies should be complemented by risk mitigation tools, revenue-certainty mechanisms, and enabling regulatory environments to attract private capital at scale.

Repurposing environmentally harmful fossil fuel subsidies can unlock significant resources for air quality projects. Fossil fuel subsidies remain one of the most significant market distortions—explicit subsidies remain at approximately US$0.5 trillion annually, while implicit subsidies, including tax breaks, total close to US$5 trillion globally. In 2020, countries like Libya and Venezuela allocated as much as 17.1 percent and 6.6 percent of their GDP respectively, to fossil fuel subsidies, which artificially lower fuel prices and hinder adopting cleaner energy alternatives. Reforming these subsidies can unlock substantial financial resources for sustainable energy investments and clean air initiatives. In Kazakhstan, reforms such as the "tariff for investment" program and carbon pricing are aiming to phase out costly subsidies while implementing social protections for vulnerable groups. This strategy is expected to reduce public spending, free up national budgets, and support projects like building modernizations and renewable energy adoption.

Financial market development is vital for diverse funding sources. Developed markets use tools like green bonds and sustainability-linked loans to support varied air quality projects, but emerging markets face challenges accessing international climate funds. The European Investment Bank has supported sustainable transport projects across the EU through its green shipping financing programs under the European Fund for Strategic Investments, but in emerging markets, the lack of sophisticated financial instruments and robust regulatory frameworks poses significant challenges. Carbon finance offers a viable alternative, as seen in Kenya's KOKO Networks, where carbon credit revenues subsidize clean cooking technologies, reducing reliance on high-emission fuels without government subsidies.

28 See the World Bank's Deep Dive presentation on the Hebei PforR Program here: https://thedocs.worldbank.org/en/doc/1344117dd7cf9ef1bfe3aaf6bfb0f366-0070012024/original/0427-China-Hebei-PforR-Deep-Dive-World-Bank-Min-Hou.pdf

Instruments such as green bonds remain underutilized and accessing international climate funds (by highlighting direct and/or co-benefits to climate change from air quality operations) is challenging, with only 5 percent reaching high-impact regions like South Asia (World Bank, 2023a). A range of instruments and involvement from banks and non-banking financial companies can ensure funding access for both large and small projects, aligning costs with the pricing of externalities.

Strong data systems and institutions are critical for effective monitoring and enforcement. Integrated data systems enhance planning and support performance-based financing. Reliable data on pollution sources improves resource allocation and accountability. Examples like Hebei's clean stove deployment highlight the importance of quantifiable indicators to build investor confidence.

Sustained commitment is required as economic growth can offset initial air quality gains. Robust institutional frameworks and market-based instruments should be adaptable to economic changes to ensure long-term impact. Integrating air quality within long-term development plans and securing continuous funding are essential for lasting improvements.

3.3.3 FINANCING MECHANISMS BY POLLUTION SOURCE

Financing mechanisms require customization based on each source's revenue potential and cost internalization capacity. Pollution sources differ in their capacity to attract private investment and demand tailored strategies for sustainable financing. Effective mitigation relies on aligning financing instruments with the distinct characteristics of emission sources across sectors.

Large point sources, like power plants and heavy industry, require high capital investments and complex regulatory interventions. These sectors typically have established revenue streams that enable them to pass costs onto consumers and internalize environmental costs through pricing mechanisms. The level of concessionality required is relatively low, with public sector involvement best directed toward policy reforms, risk mitigation, and creating an enabling environment. These sectors benefit significantly from economic instruments that internalize environmental costs and incentivize cleaner technologies. For instance, emissions pricing (such as a cap-and-trade system) has proven effective in driving pollution reduction, while DFIs can play a supplementary role, such as assisting through demonstration projects and technical assistance that help establish market viability for cleaner technologies. The United States Regional Greenhouse Gas Initiative channels revenues into pollution control and energy efficiency projects, illustrating how emissions trading programs can fund cleaner technologies while involving private capital (Blended Finance Taskforce, 2023). Public-private partnerships are also critical for large-scale projects in these sectors, allowing governments to leverage private expertise and spread financial risk for projects aimed at reducing emissions.

Diffuse and small-scale sources, such as household cooking and agricultural residue burning, present unique regulatory and financing challenges due to their decentralized and often informal nature. These sources lack the capacity to generate significant revenue and the social impact of these activities—particularly on low-income communities—necessitates strong public sector involvement. Substantial subsidies, incentive programs, and concessional financing from DFIs are crucial in these areas. Given the low capacity for private sector monetization, private capital tends to focus on supply chain solutions or microfinance options, with significant risk-sharing mechanisms provided by the public sector to make investments viable. In addition, the small ticket sizes and high transaction costs associated with financing these activities deter private sector engagement. Initiatives like the World Bank-supported Bangladesh Environmental Sustainability and Transformation (BEST) project aim to use public financing, combined with green credit guarantee funds, to incentivize SME investments in clean technologies to reduce air pollution (Blended Finance Taskforce, 2023). In Mongolia, the Ulaanbaatar Clean Air Project's stove replacement program demonstrated how tailored interventions at the household level can yield significant public health benefits by reducing indoor air pollution. Poland's Clean Air Priority Program also demonstrates the role of subsidies and concessional loans in supporting the replacement of inefficient household heating systems, reducing emissions while also lowering energy costs for homeowners.

Mixed sources, including urban transport and municipal services, require a blended financing approach that calibrates concessionality based on specific components. The revenue potential in these sectors varies: infrastructure investments, such as urban transit systems, often require significant public funding with high concessionality, whereas operations and maintenance can attract private sector interest through service charges or fees. In these cases, blended financing models are effective, combining public grants for infrastructure development with private sector participation in operational aspects. Higher concessionality should be applied to the public good components, while revenue-generating elements require lower concessionality levels. Transport sector interventions require tailored solutions; a combination of funding sources (fuel taxes and congestion charges) that generate revenue streams should ideally be complemented by financing mechanisms (risk mitigation tools, demand aggregation, and structured long-term equity and debt arrangements) that enable implementation. Success requires fiscal discipline to ensure long-term sustainability, particularly for urban infrastructure where ongoing maintenance requirements must be supported by reliable revenue streams. The Colombian Bus Rapid Transit system illustrates this integrated approach.

Regulatory levers such as emission and technology standards are essential for shaping investment demand across all pollution sources. For large point sources, clear emission limits and compliance mandates ensure private sector engagement; for small-scale and diffuse sources, fuel standards and enforcement mechanisms complement financial incentives; and for mixed sources like urban transport, low-emission zones and fleet transition mandates create stable investment environments. While market-based instruments such as cap-and-trade systems have been successful in some contexts, developing economies have relied more effectively on direct regulation, incentive-driven compliance, and targeted subsidies to drive industrial and power sector transitions. The indicative financing approaches possible for different pollution pathways are summarized in Table 3.2 below.

The level of concessionality and funding mix for air quality investments should be determined by analyzing each pollution source's revenue potential, public good characteristics, and social impacts. For high-revenue sources, commercial financing can dominate with minimal concessional funding. For diffuse sources, higher concessional support is essential due to social equity considerations and implementation challenges. Mixed sources benefit from concessional support for public goods, while revenue-generating components can leverage private capital. The estimated US$3.2 trillion investment needed for air quality improvements should employ differentiated financing, where sustainable revenue models reduce concessional dependence over time, supporting public goals. A practical starting point is to address sources where financing mechanisms such as aggregated demand

Table 3.2.
System costs of achieving the air quality and greenhouse gas targets for the different modeled scenarios in Almaty

Pollution source type	Key challenges	Enablers	Financing strategies	Examples
Large point sources (such as power plants and heavy industry)	• High capital costs for cleaner technologies • Complex regulatory requirements • Weak financial returns from emissions reduction	• Consistent emissions policies and long-term government commitments • Stronger cap-and-trade systems	• Public-private partnerships • Green bonds • Emissions trading schemes	**Regional Greenhouse Gas Initiative in the US** Proceeds from emissions trading fund clean energy and energy efficiency programs.
Diffuse and small-scale sources (such as households, agriculture, and small- and medium-sized enterprises)	• Fragmented, small-scale interventions • Limited revenue models • Lack of access to finance	• Consumer finance mechanisms • Targeted subsidies and incentives for cleaner technologies	• Microfinance schemes • Concessional loans • Results-based financing	**Bangladesh BEST Project** Clean cookstoves funded through green credit guarantee funds to reduce household emissions.
Mixed sources (such as urban transport and waste management)	• High infrastructure costs • Complex stakeholder involvement (including municipalities and private operators)	• Clear urban air quality goals integrated into city planning • Policy levers like vehicle emissions standards	• Municipal bonds • Blended finance • Congestion pricing revenues	**Colombia's Bus Rapid Transit system** Funded through municipal green bonds and supported by vehicle emissions standards.

Source: World Bank.

models or microfinance can directly enable the adopting of clean technologies. For instance, targeted financing for household energy solutions or municipal-level emissions management can show immediate results while establishing the groundwork for larger-scale efforts.

3.3.4 TAILORED FINANCIAL INSTRUMENTS AND PRIVATE SECTOR ENGAGEMENT

Mobilizing resources to address the global air quality crisis requires tailored financial instruments that effectively reduce investment risks and incentivize private sector participation. Governments and DFIs play pivotal roles in de-risking investments, fostering robust project pipelines, and implementing financial reforms. Key policy interventions, such as pollution pricing and repurposing fossil fuel subsidies, lay the groundwork for de-risking and make pollution control projects more appealing to investors. DFIs deploy a range of complementary instruments, from development policy financing for upstream reforms to results-based financing for implementation and blended finance for private sector engagement. This integrated approach ensures policy reforms and investments work together for maximum impact. Blended finance, which combines concessional public capital with private funds, is particularly useful in high-risk, low-income contexts, as it lowers entry barriers and broadens the funding base. Private-public partnerships can further leverage private sector expertise and financing for essential pollution control infrastructure, enabling shared risk and increased efficiency in project execution. In addition to blended finance, specific financial instruments play a critical role in mitigating risks and aligning incentives with environmental outcomes. For example, guarantees could attract private capital by addressing revenue uncertainties in air quality projects. Similarly, performance-based and results-based financing models, which link payments to the achievement of predefined results, incentivize service providers to achieve measurable air quality improvements. Sustainability-linked loans and green bonds further support air quality objectives by tying financial terms to the borrower's success in meeting established environmental key performance indicators, thus enhancing accountability and building investor confidence.

Blended finance approaches structured around concessional capital from public or DFI sources can mobilize larger sums for air quality projects, especially those with high initial risks or limited revenue streams. When combined with development policy financing and results-based financing, these instruments can address both structural and operational barriers, creating scalable solutions for air quality interventions. Concessional loans and grants from DFIs, like those under the International Development Association's Private Sector Window, play a critical role by blending concessional funds with commercial finance to de-risk investments, especially in low-income and fragile countries. Mongolia's Ulaanbaatar Air Quality Improvement Program demonstrates effective risk allocation through a multi-tranche financing structure, achieving a 51 percent reduction in winter $PM_{2.5}$ levels.

Guarantees further support risk mitigation, helping to address the higher perceived risks in air quality projects, which often have uncertain returns due to limited revenue models or regulatory hurdles. These instruments have proven to be effective in mobilizing private capital; for instance, each dollar of public capital deployed through guarantees can mobilize up to US$1.5 of private investment (Blended Finance Taskforce, 2023). Bangladesh's BEST project established a US$170 million Green Credit Guarantee Fund with 70 percent private sector participation, showing how credit guarantees can effectively catalyse private investment. Despite this potential, guarantees still represent a small fraction of multilateral development bank commitments, highlighting a significant opportunity to scale up the air quality financing sector. The Multilateral Investment Guarantee Agency's (MIGA) political risk guarantees offer an additional risk mitigation tool that can be leveraged to attract private capital into air quality investments. For instance, MIGA's support for KOKO Networks in Kenya and Rwanda demonstrates how guarantees can de-risk investments in clean cooking solutions, which generate carbon credits while improving air quality. This approach aligns with broader climate finance objectives and highlights the role of risk-sharing mechanisms in unlocking financing for air pollution mitigation. Integrating guarantees within a framework that emphasizes the "polluter pays" principle through the pricing of externalities ensures that private capital investments align with responsible environmental practices and make pollution reduction financially viable for industries. Early wins in financing AQM can stem from targeted applications of risk-mitigation tools or concessional funding to de-risk projects in key sectors. For instance, creating guarantee-backed financing for cleaner technologies in transport or piloting sustainability-linked loans for municipal projects can build momentum and encourage private sector participation

Performance-based financing and results-based financing are emerging as powerful tools for enhancing accountability and outcomes across sectors and could be explored for AQM. Traditional bond instruments, such as green and sustainability bonds, also offer substantial, yet largely untapped, potential for air quality financing. Although bond markets have indirectly supported environmental

Box 3.3. The Kyrgyz Republic Air Quality Improvement Project

The Kyrgyz Republic Air Quality Improvement Project, backed by a US$50 million concessional loan from the World Bank's International Development Association (IDA), addresses the significant air pollution challenges in Bishkek, particularly those stemming from residential heating.

The project focuses on strengthening air quality management, promoting clean heating solutions, urban greening, and building the capacity of government agencies. A key innovative feature of this project is its revolving fund mechanism, designed to help individual households transition from polluting heating sources, such as coal, to cleaner alternatives like electric.

The revolving fund provides sub-loans to households, allowing them to adopt cleaner heating technologies. These households, in turn, repay the fund through operational savings generated from reduced fuel consumption and lower emissions. This creates a sustainable financing cycle, ensuring that the fund is replenished and can be reinvested in further air quality improvement measures.

Concessional finance plays a vital role in ensuring the project's affordability and sustainability. The IDA's zero-interest loan, spread over 50 years with a 10-year grace period, ensures that the Kyrgyz government can finance these transitions without an undue financial burden. This combination of concessional finance and revolving fund mechanisms not only addresses a significant source of air pollution in Bishkek but also demonstrates a replicable and scalable model for financing air quality improvements in other regions. By using self-sustaining financial structures, the project reduces dependence on external capital and enhances the long-term viability of clean heating initiatives, offering a promising strategy for broader air quality management efforts.

Box 3.4.
The Bangladesh Environmental Sustainability and Transformation project

The Bangladesh Environmental Sustainability and Transformation (BEST) project exemplifies how tailored financing mechanisms can address the various roadblocks of air quality financing through targeted interventions.

The BEST project, supported by up to US$250 million in World Bank financing, illustrates a strategic approach to air quality management (AQM) that leverages private sector participation and tailored financing tools. The project focuses on key sectors that contribute significantly to pollution, such as brick kilns, municipal waste management, and rooftop solar installations. The goal is to create an enabling environment for air quality improvements by enhancing regulatory frameworks and strengthening environmental institutions.

Central to the BEST Project's strategy is the proposed US$170 million Green Credit Guarantee Fund—co-financed by the World Bank, Agence Française de Développement, and the private sector—which mitigates the risks of private investment in air pollution control projects by providing credit guarantees. These guarantees encourage private entities to finance pollution reduction measures that might otherwise be deemed too risky.

In addition to the Green Credit Guarantee Fund, the project uses other tailored financing instruments such as results-based financing (RBF) and targeted lending mechanisms. RBF links funding disbursements to measurable air quality outcomes, ensuring accountability and effective resource allocation.

Targeted small and- and medium-enterprise (SME) financing provides accessible credit to small and medium-sized enterprises involved in pollution reduction, helping these businesses adopt cleaner technologies and practices.

By integrating these diverse financing mechanisms, the BEST Project aims to serve as a model for promoting private sector investment in AQM. The combination of credit guarantees, RBF, and risk-sharing mechanisms supports both large-scale industrial projects and smaller community-based initiatives, fostering long-term sustainability and resilience in Bangladesh's environmental landscape.

projects, a more dedicated market for green bonds targeting air quality remains underdeveloped. RBF links payments to the achievement of predefined, verified results, incentivizing service providers to focus on effective project delivery. Governments and multilateral agencies have increasingly adopted RBF across water, education, and energy sectors,[29] demonstrating its potential for wider application (IBRD, 2023). In air quality projects, RBF could directly tie funding to measurable pollution reduction outcomes, aligning financial rewards with impactful interventions. DFIs could play a pivotal role in this space by supporting the creation of standardized green bond frameworks and external review processes specifically for air quality projects, thus providing clarity for private investors and establishing a precedent for dedicated air quality bonds.

Outcome bonds further enhance the potential of performance-based financing by directly aligning investor returns with achieving specific environmental goals. The World Bank's Plastic Waste Reduction-Linked Bond, issued in 2024, is an example of this approach, where investor payouts are tied to verified waste reduction and recycling outcomes in Ghana and Indonesia (IBRD, 2024). This model demonstrates how outcome-based bonds can mobilize private capital for environmental initiatives by directly linking returns to achieving verified credits or reduction targets. Adapting this structure for air quality could enable urban authorities or national governments to issue bonds tied to specific pollution reduction goals, creating a new asset class that incentivizes measurable environmental outcomes while appealing to impact-oriented investors.

Sustainability-linked debt presents another financing opportunity, where interest rates are tied to the borrower's performance against achievement of predetermined sustainability targets or key performance indicators. The Uruguay Sovereign Sustainability-Linked Bond, issued in March 2023, raised US$700 million by linking investor returns to Uruguay's performance on reducing GHG emissions intensity and maintaining native forest area.[30] This structure incentivizes performance on environmental metrics and enhances accountability for meeting national climate commitments. Although sustainability-linked debt has grown across various sectors,[31] applying it to air quality initiatives remains limited. Developing harmonized key performance indicators and metrics for air pollution reduction could make these instruments more attractive for air quality financing, incentivizing borrowers to invest in cleaner technologies and emissions abatement. Policy interventions to strengthen monitoring, reporting, and verification systems for air quality would further support the adoption of sustainability-linked debt, enhancing trust and transparency for investors and borrowers alike.

Revolving funds are a promising model for sustainable financing in air quality projects, particularly for initiatives that involve emissions reduction technologies or pollution control measures. Traditionally used in energy efficiency, revolving funds operate by using savings generated from project outcomes to replenish the fund, enabling ongoing reinvestment in new projects. This model can be adapted to support air quality interventions, such as industrial emissions control, vehicle

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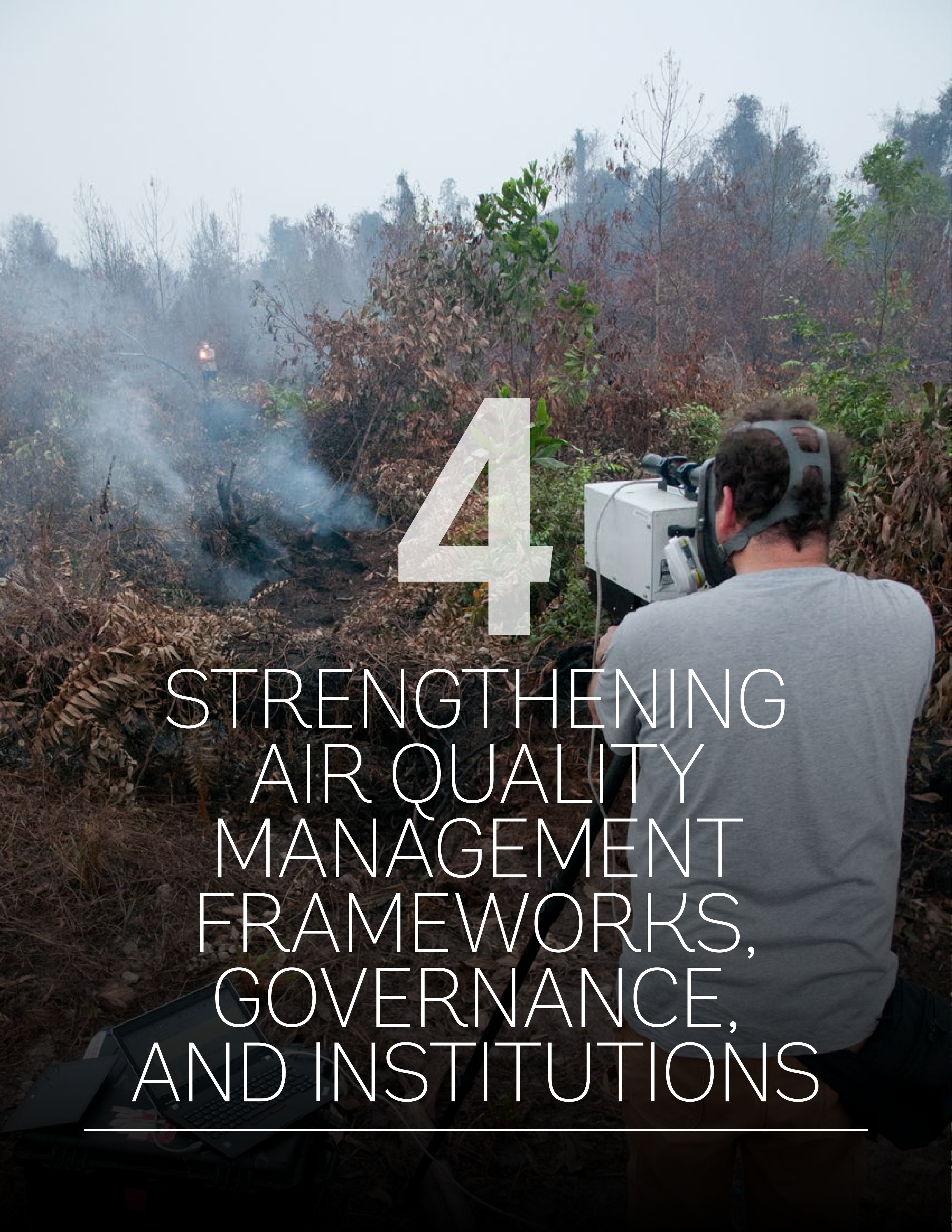
29 A learning session was held in India on RBF in government schemes and policies during the 2024 National Conference on Monitoring, Evaluation and Learning https://dmeo.gov.in/content/advancing-results-based-financing-rbf-logical-framework-performance-linked-results-and-its

30 Uruguay's latest Sovereign Sustainability-Linked Bond (SSLB) Annual Report is available at https://sslburuguay.mef.gub.uy/innovaportal/file/30672/14/sslb-annual-report-may-31st-2024.pdf

31 See the Climate Bonds Initiative website for more information on Sustainability-Linked Bond Dataset Methodology: https://www.climatebonds.net/market/SLBD

efficiency improvements, and cleaner residential heating systems. Operational savings from reduced fuel consumption and emissions reductions can replenish the fund, creating a self-sustaining financing cycle that minimizes reliance on external capital over time. The Kyrgyz Republic's Air Quality Improvement Project (Box 3.3) exemplifies this model.

Establishing dedicated clean air financing facilities by DFIs could also provide a structured stream of funding for air quality initiatives with tailored windows for specific interventions. Such facilities could enable DFIs to deploy a range of financial instruments, including green bonds, social bonds, and RBF, effectively targeting pollution sources and optimizing resource allocation (Shakti Sustainable Energy Foundation and Sensing Local, 2022). Additionally, creating dedicated project pipelines with measurable air quality improvements at an aggregate level, rather than project-specific metrics, would enhance transparency and accountability. This approach allows DFIs to direct funds towards high-impact air quality interventions, avoiding fragmented efforts and ensuring comprehensive air quality improvements. For instance, the Asian Development Bank's initiatives in the Greater Beijing-Tianjin-Hebei region and Ulaanbaatar underscore the benefits of targeted financing and policy support, showing how a coordinated approach can enhance outcomes in complex urban environments. The BEST project provides an example of tailored financing mechanisms addressing various roadblocks of air quality financing through targeted interventions (Table 3.2 and Box 3.4).



4

STRENGTHENING AIR QUALITY MANAGEMENT FRAMEWORKS, GOVERNANCE, AND INSTITUTIONS

Effective air quality management requires strong policy frameworks backed by a long-term, cross-sectoral plan, effective governance and capable, resourced institutions. Beyond all, it requires the high-level political will to act.

The key elements of effective air quality management are known and have been successfully applied in many places to manage large stationary sources and road transportation emissions. However, smaller, more dispersed area sources represent a special challenge in low-middle income contexts that require adapting traditional AQM approaches.

Designing and implementing cost-effective AQM systems can be complex and multifaceted—yet in many jurisdictions, they have been empirically demonstrated to work. Examples of effective and comprehensive AQM planning, typically undertaken by national and city governments, exist in North America, Europe, and Asia. These programs share a strong reliance on scientific information to identify key pollution sources, an iterative and cyclical process of program evaluation and assessment to ensure accountability, and several key enabling governance and institutional conditions, namely a sound legal and regulatory framework, a committed executive, nested planning arrangements, horizontal and vertical institutional coordination, and accountability and transparency.

Institutional collaboration within and across government boundaries is a prerequisite to effective AQM. While regional coordination may be challenging, it is critical to addressing the typical contribution (30–50 percent) that comes from outside a city boundary. Although the composition of source structure affecting individual cities and regions may differ, progress almost always relies on concerted action across multiple sectors. AQM is implemented in an ongoing, cyclical process to iteratively reduce emissions and assess progress across sectors and over time. It should be seamlessly integrated with climate mitigation planning and implemented both within cities and across airsheds. This section defines the elements of comprehensive AQM planning, describes the enabling institutional and governance conditions needed for AQM to thrive, and addresses the question of successful implementation approaches.

MAIN MESSAGES IN THIS SECTION

- There is no single recipe for fighting air pollution, but the five enabling conditions and eight core competencies for AQM are well established and have been applied in many different contexts.
- AQM should follow a model of self-correcting improvement and target uncontrolled sources to secure "quick wins" before implementing subsequent rules and regulations.
- AQM requires a focus across multiple scales and sectors, ranging from local geographies to multinational airsheds. Larger projects are likely to require multinational cooperation across borders to succeed.

Box 4.1. Country illustrations of various air quality management framework development strategies

The eight core competencies for air quality management (AQM) are well defined and the five key enabling conditions, cross-cutting governance, and institutional attributes for effective AQM, have been empirically determined. However, there is no single recipe for cleaning the air.

While these competencies and governance and institutional attributes have proven to be highly relevant and catalytic across countries, the process and implementation sequence can take different routes depending on each country's institutional, political, and social idiosyncrasies. Experience shows that solutions will span multiple sectors and share the same characteristics common to the most successful programs globally. However, these examples highlight noted differences in sequencing sector reforms (usually starting with the largest contributing sectors), sequencing cross-cutting governance attributes, and setting up institutional arrangements and mechanisms (often starting with legal and regulatory changes), as well as airshed approaches that vary from federal (Mexico) to confederal (European Union) to unitary (China) systems of government.

China: Since the late 1990s, China had seemingly made significant progress in initially tackling its air quality problems using a city-by-city air quality planning approach, as described in Box 2.3, that focused on (i) an emission permit and fee system for point sources, (ii) vehicle measures, (iii) urban dust measures, and (iv) mandated AQM plans for key cities with fixed targets and timelines. However, the persistent problem of severe episodes led to a strategic shift in 2013/14, recognizing that the city-by-city approach failed to continuously reduce emissions in urban areas and surrounding areas of the Jing-Jin-Ji region. This led to a series of regulations over 2013–2017 that initially targeted a variety of sources across the entire Jing-Jin-Ji region using airshed planning, including coal use (by industry, power plants, and households), industrial process emissions, vehicular exhaust, and fugitive dust (from construction sites, road dust, and other sources via regulation and tree cover), as well as secondary sources of particulate matter that comprised nearly 40 percent of total concentration levels. This shift to airshed planning was also characterized by strong regional coordination, municipal accountability, enhanced public access to monitoring and emissions data, central government funding for both administrative capacity and financial incentives for clean technology adoption (for instance, energy efficiency and renewable energy); and the removal of fertilizer subsidies to reduce ammonia contributions to secondary particle formation. These policies and finance schemes have been continuously implemented both during the 2018–2020 period and during the 14th Five-year Plan period of 2021–2025 over the expanded Jing-Jin-Ji region including Beijing, Tianjin, Hebei and parts of Inner Mongolia, Shanxi, Henan, and Shandong. As a result, China has been able to achieve significant air quality improvements across substantive parts of the North China Plain, where they have reduced average $PM_{2.5}$ concentrations over the last twelve years from around 100 $\mu g/m^3$ to approximately 35 $\mu g/m^3$ now (that is, a yearly improvement in $PM_{2.5}$ concentrations of 8.4 percent).

Mexico City: Facing a public health crisis, the government of Mexico launched the first multiyear air quality management strategy in 1990. The initial "bottom-up" series of measures targeted the transportation sector and led to significant reductions in lead and sulfur emissions through a series of fuel reforms and mandated vehicle technologies. As outlined in Box 2.5, the successive "PRO-AIRE" series of AQM programs provided more comprehensive planning with both medium- and long-term time planning horizons along with geographic coverage that extended well beyond Mexico City, recognizing that the geography of the surrounding mountains called for a regional approach. These programs, which set comprehensive air quality—and eventually climate—goals included more scientific information and set limits on the number of days that would exceed national standards. Importantly, these programs were also backed by federal and local cooperation, funded through a federal gasoline tax and, in 2014, supplemented with fees from vehicle inspections. Beyond vehicle measures, the programs also put restrictions on heavy industry and agricultural burning and reduced fuel loads to reduce forest fires. Civil society has played an indispensable role in ensuring that commitment to cleaner air in the Mexico City Metro Area is sustained. Key regulatory and capacity advances were also supported through four World Bank Development Policy Finance operations to Mexico for a total of US$2.20 billion between 2002 and 2009.

European Union: Air pollution reductions in the EU are the result of 50 years of cooperation between the nation states of Europe, both inside and outside the EU, in strategic agreements to reduce national emissions of air pollution and to improve air quality (with an early emphasis on acid deposition and sources contributing to sulfate and nitrate deposition). The decrease was accomplished mainly by creating emissions standards for major pollution sources such as power stations and for individual products such as road transport vehicles. Years of scientific research led to both the recognition that air quality improvement was beyond the control of individual member states, necessitating strong intergovernmental cooperation frameworks and viewing AQM as a routine local and national practice. Cooperation across EU member states has ensured uniformity of health protection, a common level of environmental product standards for goods, common regulations for large emitters and technology effectiveness (Best Available Techniques), and uniform reporting requirements. A lack of actual sanctions on members reduces tensions that might otherwise arise and leads to relatively constructive engagement. Cooperation was also found to be cost effective in that research and administrative costs for the necessary institutions can be shared. Over the past three decades, emissions of air pollutants have fallen across Europe. In the period between 2005 and 2020, emissions of all the major air pollutants in the EU fell by between 10 and 80 percent. During this time, the total GDP of the EU rose by over 10 percent, indicating that the downward trend in air pollution was not caused by an economic contraction and that GDP growth can be achieved without adding to the air pollution burden. It is also notable that other EU measures have been aligned with air quality goals and aims, such as the EU Green Deal and energy policies.

The experiences of these three different regions suggest that there is no silver bullet. Improving air quality takes time, as solutions require changes to policies and institutions as well as sustained political commitment over many years and across the full geography of an airshed. While these three illustrations demonstrate different starting points, they highlight the need for strong, high-level leadership, the importance of national standards based on credible scientific and robust public input, aligned fiscal policies, as well as both horizontal and vertical coordination of sectoral policies and enforcement of a sound legal and regulatory framework. Government capacities in place and availability of air quality data play also a critical role in promoting change.

Source: Narain et al., 2020; Kehew, 2021; World Bank, 2025.

4.1 COMPREHENSIVE AIR QUALITY MANAGEMENT PLANNING

Air quality management is a complex and multifaceted problem that requires skilled staff to pursue iterative and sustained implementation.

Comprehensive AQM planning for any sizable jurisdiction (be it a municipal, state, provincial, or national government) spans a wide range of skillsets requiring a corresponding range of expertise (see Box 4.2). It involves technical disciplines to establish the scale and nature of the problem (such as monitoring and modeling air chemistry), policy and planning staff to assess other associated

Box 4.2. AQMx: Defining comprehensive air quality management planning

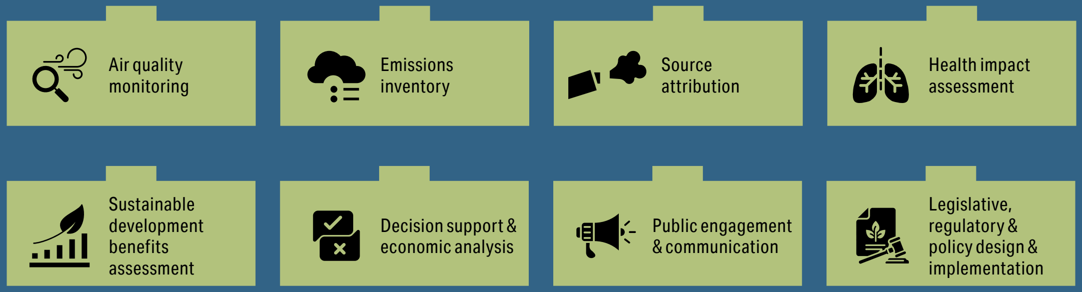
A recent global assessment shows that, apart from a lack of funding, a lack of technical capacity and other knowledge on air quality management (AQM) is the greatest challenge facing air quality managers—particularly in underrepresented regions such as Africa, Latin America, and Asia (Cody et al., 2022).

A key finding from this assessment was the need for increased collaboration and consolidation of global efforts around AQM guidance, and a need to improve and expand the delivery of guidance to address critical gaps. The UNEA-6 resolution (UNEP/EA.6/L.13) raises the need to organize and share information to build capacity in AQM and calls for the sharing of "relevant knowledge, information and expertise, best practices, interactive online tools, and data and air quality maps through the online platform". The Air Quality Management Exchange Platform (AQMx),i a component of the Climate and Clean Air Coalition's Clean Air Flagship, is designed to be a "one stop shop" for technical tools and models, data, and knowledge to build capacity among air quality managers worldwide. It has defined comprehensive AQM as comprising eight core content areas, and technical assistance and capacity benefits (through the study of economic and other development impacts) and design policy scenarios, as well as program staff to implement and enforce emission reduction measures. Carrying out these activities effectively requires extensive training, capacity strengthening, and funding. It also requires a well-coordinated approach across governments and other stakeholders to adopt, implement, and evaluate strong policies and programs. Box 4.2 defines comprehensive and integrated AQM and illustrates the challenge that many low- and middle-income countries face in lacking core capacities needed to address air pollution.

Development partners must better coordinate AQM training and service delivery to overcome the capacity gaps that LMICs face. While an increasing number of UN agencies, multilateral development banks, NGOs, and bilateral aid programs are focusing on the global air pollution challenge, AQM practitioners report that delivery of AQM guidance should be more easily accessible and harmonized across various agencies to facilitate cross-learning. Additionally, these practitioners also report that training engagements should be longer, more cohesive, and tailored to participant capacities (Cody et al., 2022).

building efforts for low-middle-income countries need to focus each of these areas of technical skill to properly address complex air pollution challenges.

Figure 4.1. Comprehensive air quality management planning



Source: An elaboration based on the Air Quality Management Exchange Platform (AQMx).

i Information about AQMx is available at https://aqmx.org/

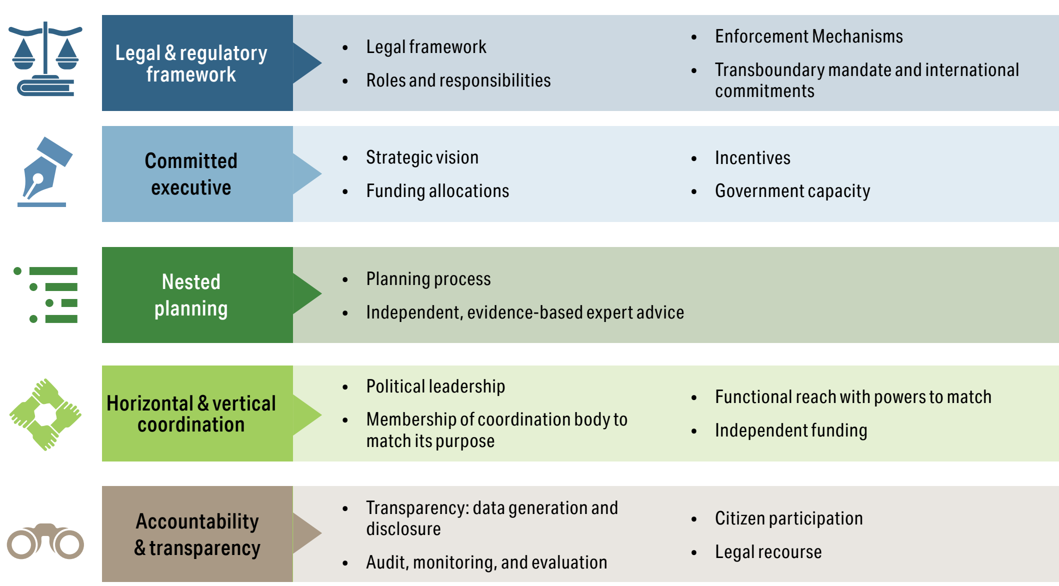
4.2 CREATING AN ENABLING ENVIRONMENT

Cross-cutting governance and institutional conditions play a major role in creating an enabling environment for AQM practices to succeed.

Based on previous analytic work and project implementation across countries, the World Bank has identified key governance and institutional factors that affect AQM performance (World Bank, 2025). These include fiscal issues like inadequate investment in planning, monitoring, and technical capabilities described in Box 4.2. Legal challenges, such as outdated environmental regulations, poor enforcement, and insufficient penalties also play a role. Governance and administrative issues are significant as well, including weak leadership on air quality, poor coordination, gaps between central planning and local execution, and low stakeholder and public involvement. Additionally, there is a general lack of economic incentives to encourage the adoption of necessary measures, specifically market-based instruments such as tradable permits, environmental fees, charges, taxes, and subsidies.

By identifying key factors, a coherent framework has been developed to assess the institutional capacity for effective and efficient AQM (World Bank, 2025). This framework consists of 18 components organized around five attributes and a set of guidance questions to carry out assessments (Figure 4.2) and attempts to identify formal institutions and actual behaviors. Emerging evidence from countries

Figure 4.2. Governance and institutional framework for assessing air quality management systems



Source: World Bank, 2025.

with various maturity levels for airshed planning and management suggests that recommendations can be built on the following governance and institutional attributes: (i) a legal and regulatory framework, (ii) a committed executive, (iii) nested planning, (iv) horizontal and vertical coordination, and (v) accountability and transparency (Figure 4.2 and Box 4.3). Changes to formal arrangements are critical, but ultimately public sector management reform is about changing the informal behaviors of agents within the public sector and therefore, the framework identifies both formal and informal agent behaviors. The framework favors organizational and institutional function over form; what ultimately matters is how institutional mechanisms fulfill their intended function, rather than whether their appearance comes across as appropriate.

A modern and effective legal and regulatory framework is the foundation of a successful and effective AQM system. It provides the formal basis for policymaking and implementing AQM standards as well as for achieving healthy air quality goals. This attribute reviews the series of laws, acts, and regulations to ensure that they (i) define the mandate for effective AQM, (ii) set the country's air quality national standards, and (iii) assign the required institutional roles and responsibilities. Additionally, it reviews the existence (and proper functioning) of compliance, reporting, and enforcement mechanisms, as well as the instruments to plan and control air pollution with a transboundary vision. UNEP's recent Global Assessment of Air Pollution Legislation finds that most countries (64 percent) embed air quality standards in either primary or secondary legislation (UNEP, 2021a). However, the higher prevalence in the EU region may indicate the role of regional conventions in supporting legal adoption of such requirements.

Properly functioning AQM systems require a dynamic, consistent, and strongly committed executive, firm leadership, and a funded mandate. Defining a long-term AQM agenda with fiscally consistent costs and expenditure frameworks needs to be explicit and championed or endorsed by high-level officials within and across layers of government. This is particularly the case if the agenda's objectives and targets are to be clearly reflected in medium-term budgets. Additionally, the technical capability of staff in selected government agencies is fundamental. A fully committed executive exhibits strong leadership backed by funded mandates and technical teams who are cognizant of the law. It implements AQM policy through multiple instruments, usually a combination of command-and-control and economic tools. This attribute reviews the existence of strong leadership, a clear vision, and an explicit and goal-oriented strategy in place, together with funding mechanisms, policy instruments, capacities and incentives (such as market-based instruments such as tradable permits, environmental fees, charges, taxes, and subsidies). For example, between 1995 and 2022, EU expenditure on environmental protection remained relatively stable, ranging between 0.7 percent of GDP and 0.9 percent of GDP, yet only a fraction of this is spent on air quality and many countries around the world make smaller investments.[32]

Nested planning assesses the planning functions in place for administering the AQM system across different airsheds and other relevant geographic areas. As well as being clearly focused on

32 Data on government expenditure on environmental protection are collected on the basis of the European System of Accounts (ESA 2010) transmission program, Eurostat, Luxembourg (accessed February 2025), https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Government_expenditure_on_environmental_protection#Evolution_of_environmental_protection_expenditure

results and properly funded, the AQM planning function should be bolstered by an official air quality planning unit (airshed, administrative boundary, or other delineation) and nested planning mechanisms between different units of the airshed zone and administrative boundaries (federal/national and state/regions, and state/regions and local jurisdictions). Even though airshed definitions vary in form and scope, countries should decide on AQM policies based on a scientific understanding of the emissions sources and their dispersion across their territories. Robust and effective AQM governance systems use scientific data to support the definition of these units and to inform the overall planning process. India had long-established city-specific Clean Air Action Plans that relied on air quality data and identifying non-attainment cities to develop city-specific short-, medium-, and long-term actions to control air pollution. However, these failed to include hard deadlines or legal mandates and did not address transboundary transport of pollution. With the introduction of the National Clean Air Programme, India now will nest individual Clean Air Action Plans under a broader State Action Plan for each state based on enhanced air quality modeling and analytics (World Bank, 2022b).

Effective coordination arrangements include vertical and horizontal coordination and generally require a high-level coordination body with a strong mandate in place. Coordination, complementarity, and concurrence of effort between different players are key preconditions to an effective AQM system. Accordingly, specific coordination bodies—with functional solutions or arrangements to facilitate and enforce aligning priorities, allocating resources, and implementing strategy—might need to be in place to ensure that all actors achieve the desired air quality outcomes. These functional arrangements enable multilevel governance between national and subnational governments (vertical) and intersectoral coordination (horizontal) across agencies and can also coordinate strategy with multinational regional air quality programs. For large countries, regional planning organizations can harmonize policies across subnational jurisdictions; for small countries, a regional airshed entity can coordinate air policy across nations. The Canadian Air Quality Management System is a unique approach for reducing air pollution that relies on collaboration by federal, provincial, and territorial governments and stakeholders, but is implemented by governmental stakeholders, each with clear roles and responsibilities. This has resulted in a decrease in lead (97 percent), SO_2 (96 percent), particulate matter (50 percent), and a significant drop in various volatile organic compounds since 1990 when monitoring began (UNEP, 2021b).

Accountability and transparency mechanisms are critical to achieving air quality objectives. Countries need to have accurate, reliable, timely, participatory, and transparent data generation systems for monitoring air quality and assessing policy effectiveness. Internal accountability (among public agencies and officials) and external accountability (to parliament, citizens, and civil society) increases knowledge and trust in air quality spending priorities and targets. This helps effectively integrate various public and private agents into the process, validate and protect resources, and allows broad citizen participation—from formulating AQM strategies to defining the desired objectives. For example, US Clean Air Act amendments authorize the United States Environmental Protection Agency to impose sanctions when an area fails to submit an adequate plan based on validated inventories or to demonstrate attainment according to monitored data by a set deadline. There are two types of sanctions: "2-to-1" emissions offsets and the withholding of federal highway funds.[33]

33 The 2-to-1 emissions offset requires newly constructed or expanded major stationary sources to reduce emissions from other facilities by twice the amount they project to emit at the new development.

Box 4.3.
Air quality management governance: enabling conditions and emerging trends across countries

Although no single country exhibits ideal governance arrangements to manage air quality, some have developed institutional arrangements (processes, mechanisms, tools, roles, and responsibilities) to address their challenges. Even though the form tends to vary by country, there are some common features and basic enabling conditions that can inspire change in other settings. Several institutional arrangements and emerging trends across public sector administrations gathered by previous World Bank analytic work are listed below. They have been developed from experience in European Union countries (Austria, Estonia, Germany, Lithuania, Slovenia, and Sweden) as well as from large federations (Australia, Canada, United States, and Mexico; World Bank, 2025). The following common features are presented along the five governance framework attributes.

Legal and regulatory framework. There is always a legal framework in place, comprising national standards for ambient air quality and sectoral pollution controls (emissions and technology standards), with a clear mandate to protect the health of the population in accordance with WHO guidelines. In EU countries, national legal frameworks usually transpose EU ambient air and emissions ceiling directives, and in some cases set more stringent standards for certain pollutants. More generally, the legal and regulatory framework in these countries makes a clear distribution of roles and responsibilities between the central government and subnational authorities. Legal frameworks establish a combination of policy tools for air quality management (AQM), including command and control and market-based instruments as well as enforcement tools (covering noncompliant jurisdictions, companies, or citizens and using several specific instruments). They tend to include specific legislation on the use of market-based instruments, such as environmental taxes and pollution charges. In some cases, the legal framework also integrates climate and air policies by setting common objectives, targets, and tools. Often, the legal framework establishes reduction targets for key pollutants and air quality standards are regularly reviewed and revised based on current country-specific scientific research and data.

Committed executive. High-level government officials usually champion air and climate policies and have clear, long-term agendas to achieve goals and targets on both fronts. In EU countries, a National Air Pollution Control Programme determines each country's long-term AQM strategy and is aligned with broader environmental policies and multisectoral development plans. Across sector ministries, air quality concerns are integrated into sector strategies and there are policies and programs in place to incentivize the adoption of cleaner technologies and production processes. More generally, the institutional setup responsible for AQM comprises multiple institutions playing complementary roles in policy making, regulation, enforcement, funding, and data and information management. There is adequate institutional, technical, and financial capacity—especially in regulatory agencies—to enable the department to perform its mandated functions. Also, the central government has specialized financing institutions to support green investments. Generally, the executive institutions in charge of AQM have the authorizing environment to influence and convene sectoral departments to implement air quality programs and plans. Some countries have also boosted public funding for environmental protection and the green transition.

Nested planning. Nesting takes place between national and subnational AQM planning instruments; and nesting between AQM planning and development instruments, as well as coordination to address local transboundary pollution, is required by law. Planning instruments for AQM identify specific measures and have access to national and international funding for their implementation. Generally, countries follow a formal process to classify regions/areas that are out of compliance, which, in turn, subjects these regions/areas to specific management and monitoring requirements by the federal or national government. AQM planning processes tend to be informed by independent, timely, and high-quality scientific research and data. Planning is backed by source apportionment, emissions inventories, and health impact estimates. In many countries outside the EU, the country has formally designated its airsheds and uses them as the key unit of analysis, planning, and air quality governance.

Horizontal and vertical coordination. Federations, in particular, will often have a mechanism (typically a regional coordination body) to coordinate policies and actions across states or regions. This mechanism has a strong mandate and political leadership to oversee progress, coordinate air quality plans, and gather scientific knowledge and data at the subnational level. The body can carry out horizontal and vertical coordination and has some level of fiscal and administrative autonomy and decision-making power and, in some cases, it can enforce AQM regulations and even resolve disputes across government actors. Often, these bodies have broad participation from the scientific community, the private sector, and civil society, and they generally disclose all data related to their activities and plans and progress on the goals. Lessons learned from federations confirm that formal bodies at the central executive level (housed at a cabinet office) that have autonomy tend to be the most effective. More broadly, countries have multiple instruments to improve vertical coordination between federal or central state governments and subnational governments on AQP policy design and implementation. Horizontal coordination is more common across countries, especially for the planning phase of AQM. In some instances, multilevel coordination platforms have emerged to improve the implementation of environmental and air quality policy through collaboration tools.

Accountability and transparency. The air quality monitoring and emissions information system is robust, with easy access to real time and reliable data across the territory, and emissions from stationary sources (industries and power plants) are also regularly captured. Often, air quality and pollution information systems are integrated and easily accessible by the public (for instance, web-based platforms that gather monitoring data to inform the public and the government on air quality in management zones in real time). Civil society and individual citizens have access to air quality information and tend to participate in policy making, while national legislation enables them to file cases against governments and/or polluters for a lack of compliance with air policy regulations. An official air quality index has been adopted and data is disclosed for public consultation and action. Air quality management networks are well established, have good coverage and integrate national, regional, and local measurement stations, while parliaments and national legislatures actively monitor the country's air quality performance and foster discussions leading to policy updates and integration. Increasingly, audit, control, and accountability institutions examine AQM plans, programs, and data. They tend to regularly review some aspects of the plans, selective programs, and quality of data, and review progress on these plans to hold the executive accountable.

Source: World Bank, 2025.

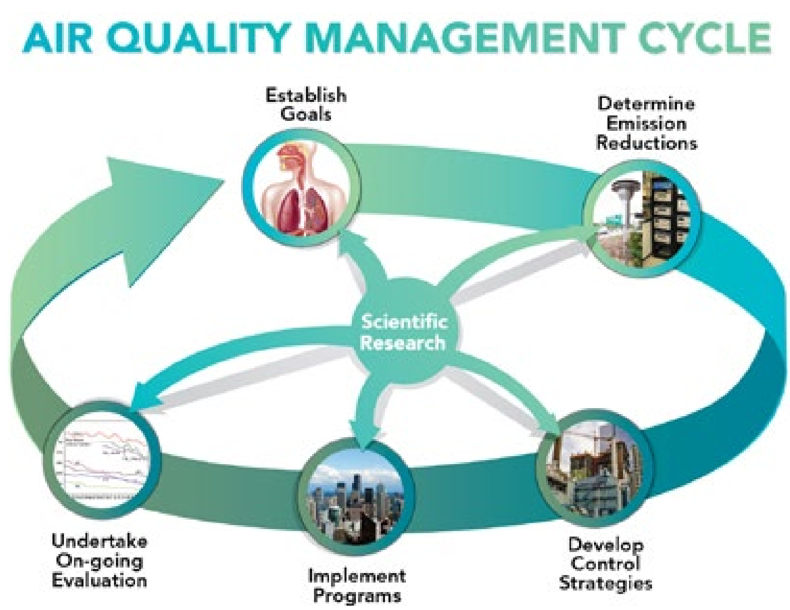
4.3 THE AIR QUALITY MANAGEMENT IMPLEMENTATION PROCESS

Air quality management is implemented in an ongoing, cyclical process that aims for constant improvement over time.

The International Standard Organization's ISO 14001 Environmental Management System standard is based on a "plan, do, check, act" structure, which creates a self-correcting system of continual improvement. This approach has conceptual appeal for scientists and engineers, but in practice, can be daunting to execute due to the extraordinary level of technical and scientific information needed to establish standards, measure key pollutants, inventory source emissions, estimate costs, and assess results. This necessarily relies on continually allocating government resources to support establishing and maintaining technical capacity for AQM over successive iterative cycles of the AQM planning process. An ISO 14001 AQM cycle—as implemented in the US and elsewhere—includes the following steps:

- **Plan:** Establish an initial goal and determine the necessary level of emission reduction.
- **Do:** Develop legally binding control strategies and implement and enforce compliance.
- **Check:** Continue monitoring and evaluating progress to see if the plan worked.
- **Act:** If the plan works, repeat the process while making necessary tweaks to standards or goals based on experience.

Figure 4.3. The air quality management cycle



Source: United States Environmental Protection Agency*

* For more on the air quality management cycle, see: https://www.epa.gov/air-quality-management-process/air-quality-management-process-cycle

Successive applications of the AQM process must account for multiple sectors to deliver progress over time. While achieving clean air goals can take decades, there are often large, uncontrolled sources that can make an initial difference (for instance, adopting technology performance standards for large emitters or banning specific polluting activities). These "quick wins" must be followed by additional rules and regulations in a subsequent round of planning. As Chapter 2 points out, the majority of global regions are facing pollution that stems from the combined contribution of emissions spanning at least three or four sectors, calling for multisector solutions as laid out in Chapter 3.

4.3.1 INTEGRATED AIR QUALITY MANAGEMENT AND CLIMATE MITIGATION PLANNING

Air quality management and climate mitigation planning and implementation should be seamlessly integrated.

Due in part to having many common sources, mitigating emissions of criteria pollutants, SLCPs, and GHGs simultaneously offers opportunities to build synergies between air pollution and climate mitigation solutions. Alignment across these two distinct planning objectives is eased by the fact that air quality interventions provide near-term and locally tangible development benefits (such as enhanced health, quality of life, and visibility) while also delivering on long-term global problems facing each jurisdiction. A major obstacle is limited awareness on the opportunities for such synergies; however, as exemplified by Mexico, this can be overcome through climate finance incentives and a focus on co-benefits for air quality (Kehew, 2021). A good starting point is to assess whether air quality standards exist, and what air quality management strategies can be derived from their exceedance. For example, focusing on energy poverty is an excellent entry point to link the air pollution and black carbon agenda and enable progress toward climate goals by addressing the immediate and severe health challenges presented by the status quo (Sánchez-Triana et al., 2023).

Ensuring synergies can reduce tradeoffs. In practical terms, integration (including the local level) can be encouraged by including AQM and climate mitigation technical and analytical work in the process of policy design and planning. AQM and climate policy documents and action plans could include targets for both air pollution and climate change (for instance, both a $PM_{2.5}$ concentration/exposure reduction and CO_2 emission reduction target) to encourage considerations of the impact of policies on both AQM and climate with the goal of achieving optimal outcomes. To maximize AQM and climate synergies, it is essential to include the air quality impacts of climate policies and measures and vice versa (Peszko et al., 2022). Box 4.4 illustrates one integrated air quality and climate change policy process, but alternative approaches[34] have also been developed that focus on prioritizing actions based on assessing the primary benefits of reducing climate and air-quality-relevant emissions, as well as the wider benefits, such as the impacts on quality of life, health, agriculture, and economy (C40 Cities, 2021). An integrated planning approach always begins at the airshed level and typically consists of the five steps discussed (Figure 4.4; Peszko et al., 2022).

34 C40 Cites, Integrated Climate Action and Air Quality Management Planning Framework, C40 Cities, New York. November 2021. https://www.c40knowledgehub.org/s/article/Clean-air-healthy-planet-A-framework-for-integrating-air-quality-management-and-climate-action-planning?language=en_US; Akbar,Sameer; Kleiman,Gary; Menon, Surabi; Segafredo, Laura. Climate-smart development : adding up the benefits of actions that help build prosperity, end poverty and combat climate change. Washington, D.C. : World Bank Group. http://documents.worldbank.org/curated/en/794281468155721244/Main-report.

Box 4.4. Integrated air quality and climate change process

An integrated air quality and climate change approach dynamically focuses on the near-term health impacts of air pollution in the most polluted airsheds while paving the way for the long-term phaseout of fossil fuels. A coherent and integrated policy framework enables plant operators and households to adjust their decisions, jointly considering air pollution and low-carbon goals.

A recent World Bank report on the interactions between air quality management (AQM) and climate change mitigation (CCM) in Kazakhstan (Zlatev et al., 2021) and the analytical work presented in Chapter 2 of this report both suggest that cost-effective, optimal strategies to address air pollution and climate change mitigation could differ. In Kazakhstan, priority measures to improve air quality in cities regard small residential stoves and boilers using coal for heating (and cooking), while priority measures for CCM involve large point combustion sources burning coal in the power sector and industry. As Chapter 2 points out, focusing on climate and energy goals alone does not achieve adequate air quality protection and an integrated approach to achieving both climate and air quality goals is far less costly than focusing on the air quality exclusively. Lessons from both studies also point to the role of fiscal instruments in closing the gap between the annualized societal costs of these programs and the full upfront investments required.

Figure 4.4. The five steps of an integrated air quality and climate change policy process

1	Air quality monitoring and population exposure	• Monitor ground-level air quality of indoor and ambient concentrations of key pollutants • Measure population exposed • Prioritize air pollution hotspots
2	Air quality objectives in airsheds	• Determine the health impact attributed to air quality • Monetize the value of impacts (optional) • Identify air quality targets for hotspots
3	Source attribution	• Conduct inventories of emission sources • Undertake source apportionment studies and pollution dispersion models to determine the airshed • Estimate greenhouse gasses co-emitted from these sources
4	Emissions-reduction measures	• Prioritize least-cost abatement measures for key emission sources in the airshed • Estimate greenhouse gas effects of these measures • Identify synergies and trade-offs between air pollution and climate change abatement measures
5	Coherent air quality managment and climate change policies	• Develop packages of targeted air quality management and climate change policy instruments to induce emittor to apply the prioritized integrated measures • Implement and enforce policies; provide access to finance; manage macrofiscal, social, and behavioral issues; review and revise

Black text denotes actions driven primarily by health considerations.
White text refers to actions that gradually introduce an integrated approach to mitigating air pollution and climate change.

Source: Adapted from Peszko et al., 2022.

Considering the implications for both air quality management and climate mitigation objectives can maximize synergies and more efficiently manage cases when divergent impacts are identified in fiscal policy. Fiscal policy is commonly used by governments to incentivize emission reductions across sectors. However, fiscal policies that target one of the issues (AQM or CCM) without considering the impact on the other might fail to identify possible divergent impacts. For instance, introducing a SO_2 tax discourages the use of coal which is beneficial for both AQM and CCM. However, introducing a carbon tax or eliminating fossil fuel subsidies to reduce GHG emissions might push households to burn more biomass, or even waste, which is detrimental to local air quality (Damania et al., 2023). Therefore, a carbon tax should go hand in hand with incentives to use cleaner fuels appropriate for the local context.

4.3.2 AIRSHED AIR QUALITY MANAGEMENT AND REGIONAL AND INTERNATIONAL COOPERATION

Shifting from the city-level air quality management to the airshed scale requires national and regional cooperation.

AQM requires focus across multiple scales. Air pollution exposure depends on both people and pollution sources, but the variability of where and how people spend their time, as well as the many types of emissions, contribute to a wide range of exposures. Agricultural workers, as well as women and children cooking over an open fire, are directly exposed to high pollution levels over a scale of only meters. Urban residents living or going to school near roads experience concentrated linear exposures along urban canyons or near highways, where exposure can decrease significantly with only a small separation from the road. In rural or desert regions, meteorological transport or winds can spread and dilute pollution across tens to hundreds of kilometers. The phenomenon of long-range transport has now been well documented and contributes to the formation of ground-level ozone pollution as well as secondary fine particle pollution that travels hundreds to thousands of kilometers (World Bank, 2023a).

Box 4.5.
South Asia regional program on air quality: shifting to airshed approach

The World Bank South Asia Region and the International Centre for Integrated Mountain Development have hosted a series of science policy dialogues to promote regional collaboration on air quality management planning across the wider airshed of the Indo-Gangetic Plain and the Himalayan Foothills region.

These dialogues, supported by potential World Bank finance programs in 12 jurisdictions and spanning five countries, have resulted in recognizing the need for an approach based on scientific targets, common methodologies and regional coordination of policy assessment. These sentiments are supported by the Thimphu Outcome, reached at the most recent dialogue, that strives to accelerate sectoral emission reduction actions, establish technical committees and working groups, share scientific knowledge and information, leverage funding in key polluting sectors to also reduce pollution, and continue to build capacity of relevant air quality agencies in the region.

Box 4.6.
Common features across collaborative watershed management and airshed management

A review of the recent status update on the Sustainable Development Goal (SDG) 6.5.2 on transboundary water cooperation provides insight into several common features between emerging concepts for airshed management and the quest for operational arrangements to manage transboundary water resources (UNECE et al., 2024).

Transboundary cooperation is indispensable and often under-appreciated. Even when not legally binding, operational agreements and airshed planning provide a technical foundation to exchange of data and deepen understanding of common issues.

Effective airshed management and transboundary water cooperation share common challenges, including lack of relevant data and information among contributing jurisdictions, resource and finance constraints, difficulty in exchanging data and technical information, and an absence of national administrative frameworks. Effective frameworks to address either water or air quality challenges must include mainstreamed integration of climate considerations, as progress for these challenges is critically linked to climate change and supports the attainment of multiple SDGs. Legal instruments, including existing national and international legislation, can serve as an important starting point to develop common or harmonized approaches to water and air resources.

Tracking progress at a global level can create more impetus for regional agreements. Data sharing, accessibility, and transparency can spur calls for local and regional action, creating political will and encouraging progress in calling for greater cooperation.

Micro- and local-scale problems may require focus on specific sectors or geographies. Factors such as meteorology, topography, and economics can affect air pollution, while urban sprawl and patterns of development influence air quality (Li et al., 2021). In general, municipal air quality management plans are vital to address specific sources that are key contributors to specific populations or even demographic groups (Clark et al., 2022). While city action plans are crucial, they also may typically only be able to address a fraction of the pollution experienced across an urban airshed if there is also a significant amount of pollution transport, yet this is the dominant mode of planning for AQM across much of the world (World Bank, 2023a).

An airshed can be generally defined as a geographical area that shares a common flow of air that is uniformly polluted or stagnant, subjecting the area to similar conditions of air pollution. For

AQM systems, defining airsheds for a region or country is fundamental as it sets the domain over which to plan coherent interventions, execute projects and programs, gather data, monitor progress, and evaluate the impact of AQM policies and programs. According to a 2025 World Bank report, the fundamental idea behind an airshed approach is to "ensure that the assessment of policies considers both the pollution generated within a specific geographic unit and any transfers of pollution into or outside its boundaries" (World Bank, 2025). Solving regional problems in the context of local action requires regional coordination, analysis and assessment, and ultimately, regional harmonization of standards and policies. Harmonization does not come without challenge, however, and unequal enforcement potential and other sociopolitical constraints can result in varied approaches to joint agreements (for instance, the US-Canada Air Quality Agreement, UNECE Air Convention, and ASEAN Transboundary Haze agreement all have very different objectives and requirements). Box 4.5 illustrates several cooperation principles being embraced by several South Asian jurisdictions seeking to achieve clean air across a broad airshed comprising the Indo-Gangetic Plain and Himalayan Foothills, whereas Box 4.6 highlights lessons learned from recent survey of nations on transboundary water cooperation.

5 CONCLUSIONS AND RECOMMENDATIONS

Policy makers face clear priorities for future action. Strengthening institutions, leveraging information and prioritizing measures across sectors, and mobilizing financing at scale are the first steps to deploy measures across sectors.

This report has shown that raising the level of ambition to cut $PM_{2.5}$ exposure is now a global development priority. Air pollution is already taking a significant health and economic toll globally, with the impact being particularly severe in developing countries. Limiting action to stated policies will both create additional costs globally and curtail development prospects of low-middle-income countries. Policy makers face clear priorities for future action. Strengthening institutions, leveraging information and prioritizing measures across sectors, and mobilizing financing at scale are the first steps to deploying measures across sectors. The recommendations in Table 5.1 to Table 5.4 stem from the policy and investment priorities discussed in the report. Organized into three priority policy packages.

5.1 STRENGTHEN INSTITUTIONS

How to get started: Governments need to demonstrate political will to act, which requires the identification of high-level clean air champions (necessarily above individual ministries – typically at the prime minister office level) with the authority and budgetary control to ensure that an established AQM framework can be supported with adequate resources and effective enforcement.

While achieving national clean air goals will take many successive iterations of clean air policy, it is critical to both "lead by example" locally with policies aimed at the most easily achieved identified below in 5.1 while simultaneously engaging neighboring jurisdictions in the airshed to ensure that broad-based action is underway across the entire source region for the pollution problems. Working across the airshed will be faster and more cost-effective, as it enables a city or region to achieve adequate air quality targets by opening a larger choice of measures, thus avoiding the need to resort to the most expensive measures within the city's limits.

Table 5.1.
Policy Package A: Strengthening institutions*

High-level objective	Policy recommendation	Instruments / actions	Example
1.1 **Strengthen the formal bases for policy making and implementation**	Develop the AQM legislative framework through a series of laws, acts, and regulations to clarify the rules of the game and influence and enforce behaviors.	• Define the mandate for effective AQM • Set the country's air quality standards and emissions targets, considering transboundary air pollution • Assign the required institutional roles and responsibilities • Establish compliance mechanisms • Create planning instruments, reporting and enforcement mechanisms • Adhere to international commitments	Air quality has improved in the European Union (EU) thanks to its regulatory framework that also fosters institutional accountability and transparency, and member states' compliance efforts. The EU provides an example of long-standing transboundary cooperation to improve air quality (within the framework of regulations issued by the EC and in response to the 1979 Long-Range Transboundary Pollution Convention) through strategic institutional agreements aiming to improve air quality and to reduce national emissions of air pollutants (through the adoption of emission standards for major pollution sources, as well as agreement on national emissions ceilings), and strong intergovernmental cooperation frameworks, as well as viewing AQM as a routine local and national practice. Institutions at EU Member States have been adapted to routinely plan, implement and monitor AQM performance and effectiveness. (Box 4.1).
1.2 **Ensure high-level championship of clean air agenda**	Enable dynamic, consistent, and committed executive leadership.	• Develop a strategic vision that supports medium-term public plans with clear goals, indicators, and assigned functions and roles • Secure funding allocations through an array of budget programs to fund all levels of AQM governance • Set up incentives via policies and market-based instruments to incentivize or penalize compliance • Build up government capacity to allow sufficient skills at the national and subnational levels.	In EU countries, the National Air Pollution Control Programmes determine the countries' long-term AQM strategies and are aligned with broader environmental policies and multisectoral development plans.

High-level objective	Policy recommendation	Instruments / actions	Example
1.3 **Establish effective multilevel planning systems**	Create modalities and planning procedures for administering the AQM system across different planning levels, including air quality management at regional and at the national level.	• Set up and implement operational planning mechanisms that are harmonized and nested across different jurisdictions • Introduce airshed approaches when appropriate • Set up independent and evidence-based expert advice via a mechanism that produces plans with independent, science- and evidence-based advice, developed in consultation with stakeholders • Perform economic benefits assessments for decision support on existing AQ policies and plans.	Successful examples of cost-effective regional air quality management through regional cooperation have been developed in China, the US and Europe (Box 4.1).
1.4 **Facilitate cross-sector and cross-government coordination**	Introduce functional arrangements to coordinate AQM stakeholders across sectors (horizontal) and between different levels of government (vertical).	• Integrate air quality into national and state programs and at the airshed and city levels via a vertical coordination mechanism • Integrate air quality into sector policies and plans and across sectors that contribute to air pollution via horizontal coordination mechanisms and beyond the environmental agencies • Ensure that coordination mechanisms have a mandate to monitor, plan, develop policies and programs; enforce AQM regulations; support the generation and dissemination of evidence-based air quality information for legislative and government decision making; independent funding to finance their operations; and links to EU cooperation mechanisms	The Canadian Air Quality Management System is a unique approach for reducing air pollution. It relies on collaboration by the federal, provincial and territorial governments and stakeholders, but is implemented by the governmental stakeholders, each with clear roles and responsibilities, and resulted in a decrease in lead (97 percent), SO_2 (96 percent), particulate matter (50 percent), and volatile organic compounds since 1990 when monitoring began.

* Box 4.3 "AQM Governance: Enabling Conditions and Emerging Trends across countries" provides further information on emerging and desirable institutional arrangements across countries. The detailed country cases provide full details.

5.2 LEVERAGE INFORMATION AND PRIORITIZE MEASURES ACROSS SECTORS

How to get started enhancing information systems: Assess the gaps in existing information systems. Countries need to have accurate, reliable, timely, participatory, and transparent data generation systems for monitoring air quality and assessing policy effectiveness. In addition to investing in generating quality information—which typically requires investments in both hard (monitoring networks) and soft infrastructure (skills and capacities), focus on how information is shared, leveraged and made public. The cross sectoral and vertical coordination necessary for clean air action; the capacity to attract private investments as well as public support to ambitious policies and measures critically depend on how air quality information is deployed.[35]

How to get started prioritizing across sectors: While identifying pollution sources can be challenging without robust monitoring systems, it should not be a reason to postpone action. There is sufficient global knowledge to begin immediately, and as more accurate information becomes available, it will enable countries to enhance the cost-effectiveness and pace of their air pollution reduction efforts.

To start: Conduct a rapid assessment of potential emissions reductions for key polluting sectors considering affordability (i.e., can subsidies be re-purposed and the private sector engaged in clean technology adoption), feasibility (e.g., do national circumstances lend themselves to transitions in specific sectors and are stakeholders amenable to shifting behavior, practices and technologies) and implementation factors (e.g., are some measures more enforceable than others). Quickly identify what can be done to reduce emissions from obvious, uncontrolled sources considering these three factors. This rapid assessment can be done with confidence even in the absence of locally specific source attribution. Lack of perfect data should not be a reason to wait. As Chapter 2 demonstrates, nearly all regions impacted by ambient air pollution have sources that span power, industry, agriculture, transportation, residential, waste and other sectors. The priority should be to start where it is possible to do so quickly. This could be where information is sufficient to chart an action or where the action has co-benefits towards economy, quality of life, and is part of other energy and climate policies.

In parallel with this rapid prioritization and action across select sectors, governments can establish a cross-sectoral assessment methodology (e.g. to prioritize sectors with consideration of synergies among air, climate, health goals considering cost and political feasibility) using agreed upon tools and data to examine how various sectors contribute to overall airshed pollution and the impacts of controlling emissions from various sectors. The engagement and participation of all sectors/ ministries is crucial, and the recommendations below will help to continue on the path to success.

35 Appendix E highlights of population-weighted $PM_{2.5}$ exposure under different policy scenarios and key priority reduction sectors by region based on regional modeling results.

Table 5.2.
Policy Package B: Leverage information to prioritize policies and measures *

High-level objective	Policy recommendation	Instruments / actions	Example
2.1 **Ground policy in sound evidence bases**	Invest in sound monitoring systems and technical capacities.	• Strengthen the coverage and quality of air quality monitoring networks • Encourage and rely on scientific assessments • Establish an iterative and cyclical process of program evaluation and assessment	China utilized increasingly advanced analyses on environmental degradation costs, detailed source apportionment, air pollution modeling, cost-effectiveness analysis, and health impact assessments to help identify the most cost-effective air quality management (AQM) strategies within airsheds, influencing AQM policies since the 14th Five Year Plan (2021-25) (Box 4.1).
2.2 **Define synergies across policy areas**	Consider the additional benefits and tradeoffs in terms of clean air outcomes of existing policies across sectors.	• Cost-benefit analyses • Sector-wide impact assessments • Integrated Climate-air quality mitigation strategies [36] • Energy and pollution pricing schemes • Identify health benefits across sectors	Supported by the World Bank, Kazakhstan analyzed an optimal air quality management (AQM) an optimal climate change mitigation (CCM), and integrated AQM and CCM strategies for Almaty and Astana. Results showed that cost-effective integrated interventions were feasible, particularly by prioritizing coal reduction for both AQM and CCM (Box 3.1). Glaciers of the Himalayas report points out that reducing black carbon in the Himalayas is a quadruple win in terms of air pollution, climate, water / energy / food security and regional resilience[37].
2.3 **Increase transparency, accountability and citizens trust**	Establish internal and external mechanisms to disclose information, track and evaluate progress, promote public participation, and hold institutions to account through adequate evidence/databases, information disclosure, and established channels for recourse.	• Increase transparency via data generation and disclosure using integrated air quality monitoring systems, source apportionment analysis, and emissions inventories ensuring mechanisms for wide-public access to data. • Promote AQ auditing, monitoring, and evaluation with mechanisms and institutions that actively audit, monitor, and evaluate the impact of policies and programs, and verify progress on legal, administrative, and political commitments and goals contained in strategies, plans, and laws • Stimulate citizen participation with systems to promote the participation of civil society in setting policy goals, budget and oversight programs • Ensure legal recourse with mechanisms that allow NGOs and citizens to seek legal recourse and to act upon it.	In Mexico, civil society played an important role in ensuring that commitment to cleaner air in the Mexico City Metro Area is sustained (Box 4.1).

* Box 4.3 "AQM Governance: Enabling Conditions and Emerging Trends across countries" provides further information on emerging and desirable institutional arrangements across countries. The detailed country cases provide full details.

36 Peszko et al., 2022; Sánchez-Triana et al., 2023.

37 This point is further supported by World Bank analyses such as Akbar et al. (2014) and Mani (2021).

The priority sectors are based on the analysis. Priority sectors may differ in individual countries and airsheds. Analysis, consultations, and prioritization sequencing of measures will be required to determine priorities at individual airshed levels.

Table 5.3.
Policy Package C: Prioritizing and integrating measures across sectors

High-level objective	Policy recommendation	Instruments / actions	Example
3.1 **Scale up clean cooking solutions**	Facilitate the transition to cleaner cooking fuels and stoves by creating the right enabling environment that addresses consumer needs in a reliable and cost-effective manner.	• Efficiency standards and consumer-acceptable designs for stoves • Assuring quality and reliability of fuel supply and stoves • Addressing behavior change through outreach • Targeted support to disadvantaged households • Guarantees for large scale suppliers • Innovative financing mechanisms for scaling up.	The Uttar Pradesh Clean Air Management Program (UPCAMP) promotes clean cooking and reducing household biomass burning through a focus on affordable liquefied petroleum gas access, improved cookstoves and induction stoves, leveraging subsidies, private sector support, and micro-financing via women's self-help groups.
3.2 **Reduce air pollution from interior space heating**	Reduce consumption of solid fuel, including biomass, in space heating through a combination of shifting to cleaner fuels, better heating appliances, and implementation of energy efficiency measures.	• Energy efficiency standards for appliances • Shift to cleaner fuels like natural gas and electricity • Retrofitting homes and buildings • New innovative financing mechanisms for scaling up	Bosnia and Herzegovina, with support from the World Bank, focused on single-family homes, by providing grants for cleaner heating solutions such as replacing polluting stoves and boilers with modern heating solutions, and energy efficiency measures like insulation and window replacement; in addition to strengthening air quality monitoring and management.
3.3 **Reduce industrial sector emissions**	Target industrial stationary sources through regulation and incentives. Focus on lightly regulated small and medium-sized enterprises where innovative solutions are needed and profit margins are likely thinner.	• Emission standards • Pollution control technologies • Cleaner production processes • Renewable energy adoption • Monitoring and enforcement mechanisms to ensure compliance.	China established emission monitoring in all main industrial sources as means for monitoring and enforcement industrial emissions (Box 2.4). European Union (EU) Industrial Emissions Directive provides an example of a comprehensive legal framework for controlling industrial air emissions.
3.4 **Abate air pollution from agricultural practices**	Repurpose national agriculture budgets to incentivize farmers to implement low-emission practices with a special focus on sustainable crop residue management, soil fertility management, efficient use of fertilizers, and nitrogen emission abatement from livestock operations.	• Crop residue burning bans and support in alternative use of crop residues • Fertilizer standards • Agricultural subsidy reform • Investments in agricultural extension and advisory services systems	From 2015 to 2020, China cut fertilizer use by nearly 13% and improved fertilizer efficiency for grain production by 2.53 percentage points through removal of fertilizer subsidies, implementing standards, promoting high-efficiency fertilizers, adopting efficient technologies, and substituting manure for chemical fertilizers when possible. Subsidies were also provided to farmers for the additional costs of these changes (Box 2.3).

High-level objective	Policy recommendation	Instruments / actions	Example
3.5 **Incentivize Avoid, Shift, Improve approaches to in transport**	Address the overall demand for transport activity by reducing the need for travel, promote a shift in passenger or freight trips from more carbon-intensive modes to less carbon-intensive modes, and improve the efficiency and quality of vehicles, operations, and fuels.	• Adopting more modern fuel and emission standards • Congestion pricing and parking management in urban areas • Low-occupancy vehicle standards • Targeted investments in mass transport infrastructure and enabling investments in multimodal logistic centers • Incentives towards fleet renewal through vehicle retirement or scrappage schemes • Investments in grid strengthening for transport electrification	Mexico City reduced transport air pollution emissions through a combination of mandating catalytic converters; removing lead from gasoline; reducing the sulfur content of diesel; strengthening a vehicle inspection program; and embracing public transport (Box 2.5).
3.6 **Curb exposure from natural sources**	Invest in nature-based solutions to curb exposure to desert and soil dust.	• Invest in adding trees and green cover to degraded landscapes • Repurpose agriculture subsidies (that incentivize the expansion of the agriculture frontier) to promote agroforestry and silvo-pastoral systems that help to decrease soil erosion • Finance urban forest • Implement strategies to reduce the risk of wildfires	Korea's Urban Wind Ventilation Forest Project creates green corridors that enhance air quality, reduce urban heat islands, and improve living conditions (Box 2.7). In Indonesia, strengthened measures for forest and peat conservation—including reduced clearing, the implementation of zero-fire policies prohibiting fire-based land clearing, peatland rewetting, and fire control—have contributed to a slowdown in land-related emissions (Box 2.8). Several programs highlight the landscape restoration and conservation, such as the Sahel RESILAND Program restoring native plant life to landscapes across the Sahel-Sahara region, the Africa Union's Great Green Wall initiative, and others (Box 2.10).
3.7 **Decrease emissions from waste management**	Eliminate waste burning and capture landfill emissions.	• Measures to stop open burning of waste in the urban areas and at open dumpsites • Building awareness among communities and waste management staff on the importance of segregation of waste at source and impacts of open burning of waste • Implementing programs for integrated solid waste management programs • Circular economy approaches starting from recycling	Egypt, with World Bank support, is addressing air pollution in Greater Cairo through measures in transport and waste management. These include investments in integrated waste management facility infrastructure; the closure and rehabilitation of existing dumpsite; and strengthening the regulatory framework for waste management. These measures are expected to achieve 20% reduction of large-scale solid waste fires.
3.8 **Leverage the potential of cities to address exposure**	Empower municipal authorities to address sources of air pollution specific to their local context and to protect vulnerable local groups, (elderly residents, children, residents with respiratory conditions, outdoor workers, and others).	• Investing in air quality monitoring and information, specifically targeting vulnerable groups during air quality emergencies • Urban development plans limiting sprawl • Enforcing standards across sectors (including construction) • Measures to protect vulnerable population groups and build the capacity of the health sector for adaptive measures.	The Energy and Resources Institute recommends a 10-point Emergency Response Plan for Delhi when $PM_{2.5}$ levels exceed 400 μg/m^3. Measures include restricting driving, high parking fees, street cleaning, halting power plants upwind of the city, stopping crop and landfill fires and imposing fines, and halting construction activities, in addition to public health measures such as closing schools and distributing masks. In India, the use of respiratory face masks during times of poor air quality could potentially decrease short-term excess mortality by 13% and reduce associated costs if 30% of Delhi residents adhere to alerts from the Air Quality Early Warning System issued by the Ministry of Earth Sciences (section 2.9).

5.3 CATALYZE INVESTMENTS

How to Get Started: The most effective way to mobilize financing for air quality is to start with sectors that have clear revenue models and proven investment track records. Deploying financial instruments like credit guarantees and blended finance can attract private capital, while concessional funding supports high-impact but harder-to-finance areas like household energy transitions.

A phased approach ensures efficient scaling: in the initial years, focus on setting up emissions monitoring, creating basic risk-sharing facilities, and financing projects with clear revenue potential. In the medium term, successful models can be scaled, dedicated financing facilities developed, and institutional capacity strengthened. In the long run, innovative instruments like sustainability-linked loans and comprehensive air quality markets can be established, ensuring long-term sustainability. Integration with climate finance further reduces costs and accelerates investment, creating early successes that build investor confidence.

Table 5.4.
Policy Package D: Mobilizing finance at scale

High-level objective	Policy recommendation	Instruments / actions	Example
4.1 **Establish market-based foundations through pricing and regulatory reforms**	Implement pollution pricing mechanisms and phase out fossil fuel subsidies while creating clear regulatory frameworks with enforceable standards and monitoring systems. Incentivize institutional building, prioritize implementing performance standards and pricing reforms for early success and building momentum.	• Phased reduction of fossil fuel subsidies • Pollution charges • Emissions trading systems • Environmental taxes • Carbon pricing • Performance standards • Monitoring systems	Nepal demonstrates how to establish effective pricing reforms: start with clear policy signals (green tax at US$1.5/ton carbon), create dedicated revenue streams (0.7% revenue increase), and measure outcomes (0.9% emissions reduction). This phased approach enables sustainable funding while building market confidence.
4.2 **Align air quality financing with climate and cross-sectoral goals**	Embed air quality objectives within climate financing frameworks while developing standardized methodologies for measuring and verifying combined outcomes. Align air quality investments with Nationally Determined Contributions (NDCs) and established frameworks like SDGs that track progress on mortality (3.9.1), clean household energy (7.1.2), and urban air quality (11.6.2).	• Green bonds with dual benefits • Climate-linked concessional loans • NDC-aligned facilities • Carbon market instruments • Joint climate-air quality funds	Kenya's KOKO Networks shows how to integrate financing streams: leverage carbon credits to reduce technology costs (80-85% for cookstoves), establish robust monitoring systems (NFC-enabled tracking), and create clear verification frameworks. This integrated approach enables rapid scaling while maintaining affordability.

High-level objective	Policy recommendation	Instruments / actions	Example
4.3 **Deploy risk mitigation measures for private investment**	Create dedicated risk-sharing facilities and credit guarantee mechanisms while establishing blended finance structures that efficiently allocate risks to appropriate parties. Enhance risk-return considerations to incentivize private participation. Develop frameworks for measuring outcomes, supported by reliable measurement, reporting, and verification systems.	• Credit guarantees • First-loss provisions • Blended finance structures • Risk-sharing facilities • Policy insurance instruments • Secured revenue contracts	Vietnam illustrates how to structure risk mitigation: establish clear market instruments first, create explicit valuation mechanisms for multiple benefits (both GHG and air quality), and develop transparent credit pricing systems. This approach reduces investment barriers while ensuring policy stability.
4.4 **Scale through tailored and sustainable revenue models**	Identify and implement source-specific financing mechanisms and create dedicated air quality financing facilities with differentiated windows for various pollution sources. Ensure alignment with broader development goals by integrating air quality financing with public health and infrastructure investments, reinforcing the economic case for sustained funding.	• Performance-based financing and results-based financing instruments such as sustainability-linked, impact, and outcome bonds, revolving funds, and green credit lines	Rwanda's Clean cooking results-based financing subsidy scheme demonstrates how to scale solutions: start with clear incentive structures, establish monitoring systems for verification, and create sustainable revenue models. This enables effective technology adoption while maintaining affordability

GLOSSARY

Air pollution in this report refers to outdoor levels of fine particulates, both primary and secondary. It is often referred to as ambient air pollution, as opposed to household (or indoor) air pollution, which is formed in indoor environments due to unvented heating and cooking stoves, tobacco smoking and combustion for other purposes. Indoor air pollution sources are major contributors into outdoor air pollution and are included in this report as such. Indoor air pollution within households is outside of the scope of this report. While other ambient air pollution, such as ground-level ozone, nitrogen oxides and air toxics are a significant concern, fine particulates are responsible for the vast majority of the burden of disease associated with air pollution.

Exposure to air pollution is measured by the annual average and population-weighted concentration of the pollutant like fine particles ($PM_{2.5}$), in a cubic meter of ambient air.

Particle pollution (particulate matter or PM) includes a mixture of solids and liquid droplets suspended in the air.

Coarse particles (PM_{10}–$PM_{2.5}$) are particles with diameters larger than 2.5 micrometers (μm) and smaller than 10 μm in diameter.

Fine particles ($PM_{2.5}$) are less than 2.5 μm in diameter. This group of particles also encompasses ultrafine particles and nanoparticles which are with diameters less than 0.1 μm.

Primary fine particles are emitted directly from a source, such as construction sites, unpaved roads, stoves, smokestacks, or fires.

Secondary fine particles are formed in chemical reactions in the atmosphere of sulfur dioxides, nitrogen oxides, and ammonia that are emitted from power plants, industries, and vehicles.

Sulfur dioxide (SO_2) is one of a group of gases called sulfur oxides. From these gases, SO_2 is of greater concern. The largest sources of SO_2 emissions are from fossil fuel combustion at power plants and other industrial facilities.

Nitrogen oxides (NO_X) mostly consist of nitric oxide (NO) and nitrogen dioxide (NO_2). It is primarily produced through combustion processes like burning fossil fuels in vehicles (the main source), power plants, and industrial activities.

Air toxics are toxic species emitted into the air that include hundreds of compounds which have been identified as having serious health effects through acute or long-term exposure.

Ammonia (NH_3) primarily originates from agricultural activities like livestock waste management and fertilizer application.

Black carbon, or soot, is an air pollutant and a component of fine particulate matter ($PM_{2.5}$) that is created when fossil fuels and biomass are burned incompletely. It is also a short-lived climate pollutant that enhances radiative forcing and temperature increase within its lifetime.

Carbon monoxide (CO) contributes to climate change indirectly by participating in chemical reactions that produce ozone, another climate change gas. The main source of carbon monoxide in outdoor air is vehicles or machinery that burn fossil fuels.

Organic carbon (OC) is considered a pollutant when it exists in high concentrations in the atmosphere, primarily as a component of particulate matter (PM). It is emitted from sources like vehicle exhaust, biomass burning, and industrial processes.

Methane (CH4) is emitted during the production and transport of fossil fuels. Methane emissions also result from livestock and other agricultural practices, land use, and by the decay of organic waste in municipal solid waste landfills.

More information is available on the United States Environmental Protection Agency's website, including an overview of greenhouse gases and a glossary for air pollution terms in the context of human health.

Sources: WHO, 2021; Zavala et al., 2018.

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APPENDICES

APPENDIX A. INPUT TABLES

Table A.1.
Population growth trends by region assumed for the scenarios

	Compound average			Population (million)			Urbanization (share of population)		
	2000-2020	2020-2030	2020-2050	2020	2030	2050	2020	2030	2050
North America	0.9%	0.7%	0.5%	496	526	578	82%	84%	89%
United States	0.8%	0.5%	0.5%	330	349	379	83%	85%	89%
Central and South America	1.1%	0.7%	0.5%	522	562	603	81%	84%	88%
Brazil	1.0%	0.5%	0.2%	213	224	229	87%	89%	92%
Europe	0.3%	0.0%	0.0%	699	701	690	75%	78%	84%
European Union	0.2%	-0.1%	-0.2%	451	447	429	75%	77%	84%
Africa	2.6%	2.3%	2.1%	1,340	1,688	2,489	43%	48%	59%
Middle East	2.2%	1.6%	1.1%	247	289	348	72%	76%	81%
Eurasia	0.4%	0.3%	0.2%	236	244	253	65%	67%	73%
Russia	-0.1%	2.0%	-0.2%	144	142	134	75%	77%	83%
Asia Pacific	1.0%	0.6%	0.4%	4,210	4,488	4,727	47%	53%	63%
China	0.5%	0.2%	-0.1%	1,411	1,436	1,375	62%	71%	80%
India	1.3%	0.9%	0.6%	1,380	1,504	1,639	34%	40%	53%
Japan	0.0%	-0.5%	-0.6%	126	120	105	92%	93%	95%
Southeast Asia	1.2%	0.8%	0.6%	667	726	792	50%	56%	66%
World	**1.2%**	**0.9%**	**0.7%**	**7,749**	**8,501**	**9,687**	**56%**	**60%**	**68%**

Source: IEA, 2021.

Notes: See Appendix C for composition of regional groupings.

Table A.2.
Real GDP average growth assumptions by region

	Compound average annual growth rate			
	2010-2020	2020-2030	2030-2050	2020-2050
North America	1.6%	2.4%	2.0%	2.1%
United States	1.7%	2.3%	1.9%	2.1%
Central and South America	0.3%	2.8%	2.6%	2.7%
Brazil	0.3%	2.3%	2.7%	2.5%
Europe	1.1%	2.3%	1.5%	1.8%
European Union	0.8%	2.1%	1.3%	1.5%
Africa	2.5%	4.2%	4.2%	4.2%
Middle East	1.7%	2.6%	3.1%	2.9%
Eurasia	1.8%	2.5%	1.6%	1.9%
Russia	1.3%	2.2%	1.1%	1.4%
Asia Pacific	4.7%	4.9%	3.1%	3.7%
China	6.7%	5.2%	2.9%	3.6%
India	5.1%	7.1%	4.4%	5.3%
Japan	0.4%	1.1%	0.7%	0.8%
Southeast Asia	4.2%	4.9%	3.2%	3.8%
World	**2.6%**	**3.6%**	**2.7%**	**3.0%**

Source: IEA, 2021.

Notes: Calculated based on GDP expressed in year-2020 US dollars in purchasing power parity terms.

APPENDIX B. CLEAN AIR, ENERGY AND CLIMATE POLICIES AND MEASURES CONSIDERED IN THE ANALYSIS

Table B1 lists the new energy policies enacted, implemented, or revised since the publication of the World Energy Outlook 2020. Policies already considered in previous editions of the World Energy Outlook are not listed due to space constraints. Some regional policies have been included if they play a significant role in shaping energy on the global scale, such as regional carbon markets, standards in very large provinces or states, and so on. The table does not include all policies and measures, rather highlights the policies most prominent in shaping global energy demand today, while being derived from an exhaustive examination of announcements and plans in countries around the world. A more comprehensive list of energy-related policies by country can be viewed on the IEA Policies and Management Database.[32]

32 Policies and Management Database. International Energy Agency (IEA), Paris, France. https://www.iea.org/policies

Table B.1.
Energy policies and measures assumed in the International Energy Agency's Stated Policies (STEPS) scenario (2021) and included in this report's Stated Policies scenario (2040)

World region	Energy policies and measures assumed in the International Energy Agency STEPS scenario (Source: IEA 2021)
Argentina	• Strengthened energy efficiency building codes and mandatory efficiency labelling for new social housing.
Australia	• Energy-related recovery measures, notably public investment in hydrogen and carbon capture, utilization, and storage • Investments from the Modern Manufacturing Initiative • Funding for energy efficiency measures, including energy rating labels • The State of Victoria 2020–2021 budget for funding includes energy-efficient retrofits and rooftop solar expansion via the Solar Homes program • In the State of Victoria, the government's net-zero emissions vehicles roadmap and Electric Vehicle Action Plan support recharging infrastructure.
Benin	• Minimum performance standards and energy labelling system for lamps and unit air conditioners.
Brazil	• Energy efficiency guarantee fund.
Canada	• Energy provisions in the 2020 Healthy Environment and a Healthy Economy Plan • Spending in the Hydrogen Strategy and Strategic Innovation Fund Net Zero Accelerator • 2021 COVID-19-related recovery public investment in public transit infrastructure, electric vehicle infrastructure, and other measures • Reach nearly 90 percent non-emitting renewables generation by 2030 • Phase out conventional coal-fired plants by 2030 • Funding to decarbonize industry, which includes scaling up clean technology, supporting the production of low-carbon fuels, and introducing a hydrogen strategy • Strategic Innovation Fund to spur innovation of clean technologies and emissions reduction solutions and their large-scale deployment • Efficiency financing (second phase: financing for community energy transitions) • Implementation of updated appliance efficiency standards • A public transport infrastructure fund to improve and expand public transit, including buses • Provinces of Quebec and British Columbia aim to phase out all new sales and registrations of internal combustion engine passenger vehicles by 2035 and 2040, respectively.

China	• "Made in China 2025" transition from heavy industry to higher value-added manufacturing
	• "Made in China 2025" targets for industrial energy intensity
	• 14th Five-Year Plan:
	  • Reduce the CO_2 intensity of the economy by 18 percent from 2021 to 2025
	  • Reduce the energy intensity of the economy by 13.5 percent from 2021 to 2025
	  • 20 percent non-fossil share of energy mix by 2025
	  • 25 percent non-fossil share of energy mix by 2030
	  • 70 GW nuclear generation by 2025
	  • Indicative target of 26 percent of electricity consumption from non-hydro renewables and 40 percent from total renewables sources by 2030
	  • Over 1,200 GW solar and wind installed capacity by 2030.
	• Nationally Determined Contribution:
	  • Aim to peak CO_2 emissions before 2030
	  • Lower CO_2 emissions per unit of GDP by 60 percent from 2005 levels.
	• Standard for maximum energy consumption per square meter in buildings
	• Green and High-Efficiency Cooling Action Plan
	• Minimum performance standards and energy efficiency labelling for room air conditioners
	• Corporate average fuel consumption target of 4.0 liters/100 km for 2025 and 3.2 liters/100 km for 2030
	• Pilot/demonstration cities reward scheme for fuel cell electric vehicles and exemption of vehicle purchase tax for zero emissions vehicles

World region	Energy policies and measures assumed in the International Energy Agency STEPS scenario (Source: IEA 2021)
China	• New Energy Automobile Industry Development Plan (2021–2035) • National railway investments.
Colombia	• Energy provisions in the Ten Milestones in 2021 plan.
Egypt	• Minimum performance standards for incandescent lamps.
European Union	• European Green Deal provisions related to clean energy transitions and detailed spending and implementation measures in the Fit-for-55 package • Energy provisions in the Recovery and Resilience Facility and other recovery plans are considered at EU member country level, including major provisions for renewables, efficiency in buildings, and low-carbon transport • Coal phase-out plans considered in 16 member states, notably in Germany, Greece, Hungary, Romania, and Spain • Early retirement of all nuclear plants in Germany by the end of 2022 • Strengthening national energy and climate plans, notably offshore wind targets • Spending provisions for the New Industrial Strategy to support green and digital infrastructure, boost industry competitiveness, and enhance strategic autonomy • Country-level incentives for industrial efficiency incentives and targets • Country-level spending on green industry pilots, circular economy, and hydrogen • EU Recovery and Resilience Facility flagship area "Renovate" for energy efficiency in buildings • Country-level incentives for renovation and appliance upgrades, new building codes, and clean heating incentives and investment • The national recovery and resilience plans of EU member states support green mobility, railways, electric vehicles, and charging infrastructure.
India	• 450 GW renewables capacity by 2030 and 60 percent of total installed capacity being renewables by 2030 • National Mission on Enhanced Energy Efficiency • "Make in India" campaign to increase the share of manufacturing in the national economy • National Hydrogen Mission • New power distribution scheme reforms and public investment • COVID-19-related recovery measures, notably those ensuring energy access for vulnerable households and firms and public investment in urban transport infrastructure • Draft liquefied natural gas policy targets • Achieve electricity generation targets by 2030 in the draft 6th Strategic Energy Plan excluding additional policies under consideration (as of August 2021) • Cooling Action Plan. Standards and labelling for light commercial air conditioners, freezers and light bulbs • Energy efficiency labelling for residential buildings for renters and homeowners • Urban and public transit investments • Partial implementation of 20 percent bioethanol blending target for gasoline and 5 percent biodiesel in 2030.
Indonesia	• 23 percent share of renewable energy in primary energy supply by 2025 and 31 percent by 2050 • 30 percent of capacity additions from new and renewable energy sources under the National Electricity Supply Business Plan 2019–2028 • Introduction of the B30 program to increase biodiesel blends to 30 percent in gasoil.
Japan	• Achieving lower range targets for renewables in the draft 6th Strategic Energy Plan under the Basic Act on Energy Policy • Public spending on clean energy innovation: 2021 national budget • Subsidies for industry and commercial energy efficiency investments • Support for the introduction of high-performance ventilation equipment • Revised retailer labelling system • Eco-car tax break and subsidies for vehicles and National Budget 2021 for supporting electric and fuel cell vehicles.
Morocco	• Minimum performance standards and labelling for appliances • Mandatory energy efficiency audits for services.

World region	Energy policies and measures assumed in the International Energy Agency STEPS scenario (Source: IEA 2021)
New Zealand	• Investment supported by the Decarbonizing Industry Fund • Incentives for clean heating in the Warmer Kiwi Homes program.
Nigeria	• Minimum performance standards for refrigerators, air conditioners, central heating/cooling systems, and space heating.
Norway	• National Transport Plan supporting railways and the maritime sector.
Philippines	• No new coal building construction except for those already approved or under construction.
Rwanda	• Minimum performance standards for air conditioners and refrigerators.
South Korea	• Korean New Deal clean energy spending • 14th long-term natural gas supply and demand plan (2021–2034) • Increase renewable power capacity to 35 percent and decrease coal-fired and nuclear power capacity by 2034 under 9th Basic Energy Plan • Funding for smart and green industrial complexes, including monitoring of emissions and energy generation and consumption (Korean New Deal) • Support for energy audits in older buildings • Rebate for purchase of appliances entitled to energy efficiency grade 1 • Korean New Deal: Retrofit school buildings to integrate solar power; retrofit public rental homes, recreational, and healthcare facilities; and construct energy-efficient day-care centers and sports facilities • Subsidy scheme for supporting electric vehicles • Investment in urban and mass transit • Partial implementation of target for zero emissions vehicles: one-third of new passenger car sales in 2030 are electric vehicles or fuel cell electric vehicles.
United Kingdom	• All spending in the UK Ten Point Plan and the 2020 Energy White Paper • Provisions of the North Sea Transition Deal • Phase out of traditional coal-fired power by 2024 • Ten Point Plan, with up to 40 GW offshore wind capacity by 2030 • Electrification component of the 6th Carbon Budget • The Industrial Energy Transformation Fund provides grant funding for energy efficiency projects • Low Carbon Heat Support and Heat Networks Investment Project • Various retrofit incentive schemes for improving buildings efficiency as part of Plan for Jobs • In 2030, implementation of a ban on new gasoline and diesel cars and vans • Hybrid vehicles to be phased out from 2035 • Ten Point Plan support for zero emissions vehicles, green ships and aircraft, and public transport. Active Travel England investment in walking and cycling infrastructure.
United States	• Energy provisions in the CARES Act, other COVID-19 recovery measures and the Consolidated Appropriations Act 2021 • 100 percent carbon-free electricity or energy targets by 2050 in 20 states plus Puerto Rico and Washington, DC. • 30 GW offshore wind capacity by 2030 • Extension of renewable tax credits for solar and onshore and offshore wind • Nuclear compensated with zero emissions credits in five states • Investments from a Department of Energy program to decarbonize manufacturing in the United States • Updated minimum energy performance standards for central air conditioning and heat pumps • Training program for workforce that enables energy efficiency improvements • In California, the target is to achieve 100 percent new zero-emission passenger car and light truck sales by 2035, as well as to achieve a zero emissions medium- and heavy-duty truck fleet by 2045.
Vietnam	• 18 GW installed wind capacity by 2030 under draft Power Development Plan VIII • Minimum performance standards and labelling for appliances and lighting in residential and commercial buildings.

Source: IEA, 2021.

Table B.2.
Air quality policies and measures assumed in the Stated Policies scenario (2040)

This table presents examples from the comprehensive database that the GAINS model holds of national and international air quality policies and regulations related to air pollutant emissions that are in force in the various countries and regions.

World region	Air pollution control policies, measures, standards and regulations
Argentina	• Argentina's 2005–2025 National Strategy of Solid Waste Management (ENGIRSU). [33] • National Action Plan for Air Pollution (Resolution 1327/2014). • National Law on Air (No. 20,284, 1973). • As of January 1, 2018, all new heavy-duty vehicles and engines were required to comply with the Euro V standard.[34] The Euro IV standard was adopted in 2011 but never implemented, so Argentina jumped directly from Euro III to Euro V implementation. • Argentina offers three grades of diesel fuel: Grade 1 (AGRODIESEL) for agricultural use, Grade 2 (GASOIL COMUN) for standard diesel vehicles, and Grade 3 (GASOIL ULTRA) as the highest quality. Initial sulfur limits were 3000 ppm for Grade 1, 1500/2500 ppm for Grade 2, and 500 ppm for Grade 3; current limits are now 1000 ppm, 30 ppm, and 10 ppm, respectively. [35]
Australia	• Air quality legislation/programs[36] National Environment Protection Measures (NEPMs). There are four NEPMs related to air quality: the Ambient Air Quality NEPM, the Air Toxics NEPM (provides monitoring protocols and investigation levels for BTEX and PAH), the NEPM for Diesel Vehicle Emissions NEPM (provides guidance for managing emissions for on-road diesel vehicles), and the National Pollutant Inventory NEPM (provides the community, industry and government with free information about substance emissions in Australia). Legislation relevant to managing air quality and administered at the national level includes the Fuel Quality Standards Act 2000 and the Motor Vehicles Standards Act 1989. • Fuel quality: legislation that regulates fuel quality with the aim of reducing pollutants and emissions while also facilitating better engine technology and emission control technology. • Fuel sulfur content: 10 ppm in automotive diesel, 50 ppm in premium unleaded petrol and 150 ppm in unleaded petrol. • On April 9, 2024, Australia adopted Euro 6d-equivalent exhaust and evaporative emission standards for the light-duty vehicles, including passenger vehicles and light commercial vehicles up to 3.5 tons of gross weight (Khan and Yang, 2024). The transition to the new standard will take place between December 1, 2025, and July 1, 2028.
Benin	• Air quality is regulated under the environmental norms for air quality.[37] • Fuel lead content has been restricted since 2004, with only unleaded gasoline allowed. • Restrictions on used car importation include a 10-year age limit for light-duty vehicles and 13 years for tourism vehicles (since December 29, 2000). Emission controls are required but unspecified, and a pre-importation roadworthiness inspection is mandatory. • Some waste management policies and regulations exist in the country. However, not all waste streams are adequately addressed.
Brazil	• The National Program for Control of Air Quality (1989) established strategies for setting national air quality standards and emission limits at the source. In 1990, it set maximum emission limits for external combustion processes. • The Air Pollution Control Program for Motor Vehicles (PROCONVE)[38] includes the development of annual inspection and maintenance programs to ensure vehicles are maintained to original specifications and to prevent tampering with emission systems. PROCONVE standards for light-duty vehicles are influenced by both US and EU regulations, with some differences in limits and testing. Heavy-duty engine standards are based on European regulations. • PROMOT (Air Pollution Control Program for Motorcycles and Similar Vehicles).

33 Argentina's 2005-2025 ENGIRSU is available at https://www.argentina.gob.ar/interior/ambiente/control/estrategia-nacional

34 For more information on the Euro V standard, see https://www.transportpolicy.net/standard/argentina-heavy-duty-emissions/

35 Argentina's diesel fuel regulations are available at: https://dieselnet.com/standards/ar/fuel.php

36 For more information on Australia's country-level policies that impact air quality, see the Australia Air Quality Policy Matrix at: https://wedocs.unep.org/bitstream/handle/20.500.11822/17038/Australia.pdf

37 Benin's Air Quality Policy Matrix is available at: https://wedocs.unep.org/bitstream/handle/20.500.11822/17149/Benin.pdf

38 For more information on Brazil's emission standards for motor vehicles and engines, see https://dieselnet.com/standards/br/

World region	Air pollution control policies, measures, standards and regulations
Canada	• Canadian Environmental Protection Act, 1999. • Base-level Industrial Emissions Requirements. • On-Road Vehicle and Engine Emission Regulations, 2003. • Sulfur in gasoline regulations limit the sulfur content of gasoline to 12 mg/kg on January 1, 2020.[39] Alternatively, gasoline producers and importers can elect to apply a pool-average sulfur limit, in which case the pool-average limit becomes 10 mg/kg, with a never-to-be-exceeded batch limit of 80 mg/kg. • Canada's Sulfur in Diesel Fuel Regulations limit the sulfur content of diesel fuel for on-road and various non-road applications to a maximum of 15 ppm. • Fuel lead content: All on-road vehicles use lead-free gasoline.
Chile	• The first standards for vehicles were introduced in 1992 for Santiago and were expanded nationally in 1994. These are based on US legislation. • Since 2005/06, there are two alternative emission compliance options: (i) US-based emission standards, with EPA Tier 3-based standards effective from 2022, and (ii) European-based emission standards, with Euro 6-based standards effective from 2022. • No on-board diagnostic requirements are indicated in Chile's emission standards. • Legislation around sulfur content in fuels was confirmed in July 2024 with March 30, 2025, set as the date for 10 ppm sulfur gasoline and diesel fuel required to be available nationally.
China	• Third Air Pollution Control Plan 2023 (reducing emissions of NO_X and volatile organic compounds, setting emission caps for both pollutants). • Law on Air Pollution Prevention and Control 2022. • Three-Year Action Plan for Winning the Blue-Sky Defense Battle, 2018. • National Air Action Plan 2013 (including strengthening industrial emission standards, phasing out small polluting factories, phasing out outdated industrial capacities, upgrading industrial boilers, promoting clean fuels in the residential sector, and strengthening vehicle emission standards). • Revised Emission Standard for Thermal Power Plants (GB 13223-2011). • Chinese emission standards for new passenger cars and light-duty commercial vehicles up to China 6 are based on European regulations. • As of January 1, 2020, ship fuel in Chinese waters for international voyages must have a sulfur content under 0.50 percent mass by mass[40] In inland river emission control areas, the limit is 0.1 percent mass by mass, extending to Hainan waters by 2022.
Colombia	• Emission regulations for industries: Decree 02 of 1982 governs the volume and concentration of particulate matter, SO_2, and NO_2 that may be emitted, based on energy consumption. • Emission standards for vehicles from model year 2010 onward are defined in Resolution 910 of 2008, covering light-, medium-, and heavy-duty vehicles, with a focus on on-road vehicles. Resolution 1111 of 2013 updated these regulations by introducing Euro 4/IV and EPA Tier 2/2010 standards and added limits for emissions from natural gas and liquefied petroleum gas (LPG) heavy-duty engines. In 2019, Law 1972 proposed further reducing emission limits for new diesel vehicles to Euro VI or its equivalent. [41]In 2023, newly manufactured or imported diesel, LPG, and liquefied natural gas heavy-duty vehicles will have to comply with Euro VI standards.[42] • Law 1972 of 2019 proposes a maximum of 15 ppm starting January 1, 2023, and 10 ppm starting December 1, 2025. The maximum sulfur level allowed in gasoline was set at 300 ppm in 2011.
Egypt	• Egypt regulates gasoline quality with a sulfur content of around 500 ppm and has significantly transitioned from leaded to unleaded gasoline, with 95 percent of the country's gasoline now unleaded. • Egypt's Lead Smelter Action Plan[43] aims to reduce emissions from lead smelters by promoting cleaner technology and relocating smelters away from populated areas. • Fuel lead content: Only unleaded fuel is available for sale.

39 For more information on Canada's sulfur in gasoline regulations, see https://www.canada.ca/en/environment-climate-change/services/managing-pollution/energy-production/fuel-regulations/sulphur-gasoline.html

40 Available at: https://www.imo.org/en/MediaCentre/PressBriefings/pages/34-IMO-2020-sulphur-limit-.aspx

41 Colombia's emission standards for on-road vehicles and engines are available at https://dieselnet.com/standards/co/

42 For more information on Colombia's emission standards, see https://www.transportpolicy.net/region/south-america/colombia/

43 Egypt's Air Quality Policy Matrix is available at: https://wedocs.unep.org/bitstream/handle/20.500.11822/17186/Egypt.pdf

World region	Air pollution control policies, measures, standards and regulations
Egypt	• On-road testing of vehicles with mobile emission analyzers has been enforced • Implementation of the national strategy for integrated solid waste management at the governorate level. Used car import restrictions: Imported used cars are limited to a maximum age of three years. • Vehicle emission limits: Euro 2 and Euro 3 emission standards apply.
European Union	• The best available technique requirements for industrial processes according to the provisions of the Industrial Emissions directive. • Current practice including the Code of Good Agricultural Practice. • Directive 96/69/EC (carbon canisters). • Directive on Industrial Emissions for large combustion plants, including the recent large combustion plant best available technique conclusions (derogations and opt-outs included according to information provided by national experts). • Directive on the sulfur content in liquid fuels. • For heavy-duty vehicles: All Euro standards, including adopted Euro V and Euro VI, becoming mandatory for all new registrations from 2009 and 2014 respectively (595/2009/EC). • For heavy-duty vehicles: Euro VI emission limits becoming mandatory for all new registrations from 2014 (DIR 595/2009/EC). • For light- and heavy-duty vehicles: Euro standards as for NO_X. • For light-duty vehicles: All Euro standards, including adopted Euro 5 and Euro 6, becoming mandatory for all new registrations from 2011 and 2015 onwards, respectively (692/2008/EC), (see also comments below about the assumed implementation schedule of Euro 6). • For mopeds, motorcycles, light- and heavy-duty vehicles: Euro standards as for NO_X, including adopted Euro 5 and Euro 6 for light-duty vehicles. • For motorcycles and mopeds: All Euro standards for motorcycles and mopeds up to Euro 3, mandatory for all new registrations from 2007 (DIR 2003/77/EC, DIR 2005/30/EC, DIR 2006/27/EC). • For non-road mobile machinery: All EU emission controls stages as for NO_X. • For non-road mobile machinery: All EU emission controls up to Stages IIIA, IIIB and IV, with introduction dates by 2006, 2011, and 2014 (DIR 2004/26/EC), depending on machine category and engine size. • Fuel quality directive 2009/30/EC on the quality of petrol and diesel fuels, as well as the implications of the mandatory requirements for renewable fuels/energy in the transport sector. • Fuels directive (Reid vapor pressure)[44] (EN 228 and EN 590). • IPPC directive for pigs and poultry production as interpreted in national legislation. • MARPOL Annex VI revisions from MEPC57 regarding NO_X emission limit values for ships. • MARPOL Annex VI revisions from MEPC57 regarding sulfur content of marine fuels. • National legislation and national practices (if stricter). • National legislation including elements of EU law, for instance, Nitrates and Water Framework Directives. • National legislation, e.g., Stage II (gasoline stations). • On evaporative emissions: Euro standards up to Euro 4 (not changed for Euro 5/6) (DIR 692/2008/EC). • Products directive (paints). • Solvents directive. • Stage I Directive (liquid fuel storage and distribution).
India	• India's National Clean Air Programme focuses on strict implementation of mitigation measures, enhanced air quality monitoring and increased public awareness and capacity building (MoEFCC, 2019). • Environment (Protection) Amendment Rules, 2015 (MoEFCC, 2015). • Renovation and Modernization of Thermal Power Stations (CEA, 2019). • All new brick kilns shall be allowed only with a zigzag or vertical shaft method of brick making (MoEFCC, 2018a). • New emission standard norms of SO_2 and NO_X for five industries: ceramics, foundry industries (furnaces based on fuel), glass, lime kilns, and reheating furnaces (MoEFCC, 2018b). • Ban on pet coke and furnace oil in the industrial sector in National Capital Region states (including Delhi, Haryana, Rajasthan, and Uttar Pradesh; MoEFCC, 2018c)

44 Reid vapor pressure is a measure of a fuel's volatility.

World region	Air pollution control policies, measures, standards and regulations
India	• Auto Fuel Vision and Policy 2025. • Bharat Stage VI emissions norms from 1st April 2020. • Bharat (Trem) Stage I–III A emission standards for diesel agricultural tractors. • Bharat (construction equipment vehicles) Stage II–III emission standards for diesel construction machinery. • Bharat (construction equipment vehicles/agricultural machinery) Stage IV–V emission standards. • Bharat (construction equipment vehicles/agricultural machinery) Stage IV–V useful life periods. • Ban on open burning of waste in Indian cities. • Ban on crop residue burning in five states: Punjab, Haryana, Rajasthan, Uttar Pradesh, and Delhi. • Construction and Demolition Waste Management Rules, 2016. • Hazardous and Other Wastes (Management and Transboundary Movement) Rules, 2016. • Plastic Waste Management Rules, 2016. • Solid Waste Management Rules, 2016. • Plastic Waste (Management and Handling) Rules, 2011.
Indonesia	• Actions to prevent open burning of municipal waste and/or agricultural waste. • Regulation (PP) No. 41/1999[45] specifies ambient air quality standards, emission standards for industries and vehicles, and Pollutant Standard Index. • The Ministry of the Environment (MoE) has regulations for industrial emissions. Regulation No. 21/2008 requires thermal power plants to install a continuous emission monitoring system and report emissions. Decree No. 13/1995 sets air emission standards for large industries. Operators must control emissions and report results to the local government and MoE. • MoE Regulation No. 21/2008 concerning Emission Standard for Thermal Power Generation Activities. • Open burning of waste is prohibited (1999 Forestry Law). • Promotion of cleaner cooking fuels and clean cook stoves. • Euro 4 implementation in Indonesia under the Regulation of Ministry Environment and Forestry No. P. 20 /MENLHK /SETJEN/KUM.1/3/2017.[46] • Restriction on used car importation: Banned.
Japan	• National Air Quality Policy: Air Pollution Control Act (amended in 2015). • Air quality legislation/programs. • Air Pollution Control Law[47] (emission control standards for stationary sources); Automobile NO_X/PM Law; Dioxins Law; Prefectural (subdivisions in Japan) standards and total mass emission control standards for stationary sources, and governors implement improvement orders of air pollutant emitters; air pollutant emitters must have a pollution control manager in the factory; Basic Law for Environment provides framework for environmental policy). • Actions to prevent open burning of municipal waste and / or agricultural waste. • Emission regulations on soot and dust for waste incinerators, 1998. • Japan Motor Vehicle Emission Standards. • Fuel sulfur content: 10 ppm. • Small installation emissions regulations.
Mexico	• Mexican emission requirements for new vehicles and engines comply with either the US or European emission standards. • From 2006, heavy-duty truck and bus engines require compliance with US 2004 or Euro IV-equivalent standards effective July 2008. In 2014, requirements to meet US 2010 or Euro-VI were published. In 2018, emission standards were aligned with US 2010/Euro VI effective from 2021, with a US 2007/Euro V transition period. • Gasoline and gaseous fueled engines are tested using the EPA Federal Test Procedures and must meet the US EPA-based emission standards. Natural gas engines can alternatively be tested with the European ETC test and meet the Euro IV/V emission standards.

45 "PP" stands for peraturan pemerintah (government regulation). Indonesia's Air Quality Policy Matrix is available at: https://wedocs.unep.org/bitstream/handle/20.500.11822/17217/Indonesia.pdf

46 For more information on the emission standards that apply in Indonesia, see https://hasgara.com/news/euro-4-emission-standards-that-apply-in-indonesia/

47 Japan's Air Quality Policy Matrix is available at https://wedocs.unep.org/bitstream/handle/20.500.11822/17224/Japan.pdf

World region	Air pollution control policies, measures, standards and regulations
Mexico	• For cars and light-duty trucks, the model year 2004 and later standards are based on US Tier 1 or 2 standards and Euro 2/4 limits. Vehicles meeting these standards are also required to be equipped with on-board diagnostics. • Fuel quality standards also apply, specifically requiring that sulfur content for gasoline is 30 ppm average and 80 ppm maximum, and diesel fuel within 15 ppm.
Morocco	• Fuel (diesel) sulfur content is regulated at a maximum of 50 ppm. • Fuel lead content: Only unleaded fuel is sold in the country. • Age restriction on importing used cars is at five years. • Law 28-00 on waste management and disposal governs and provides the general framework for the sector in Morocco. • Emissions legislation in Morocco is issued by the Ministry of Equipment and fuel specifications are regulated by the Ministry for Energy Transition. Euro 6 and Euro VI emissions standards apply from January 1, 2023.[48]
New Zealand	• Air quality legislation[49] includes National Environmental Standards that cover: (i) toxic emissions: banning certain activities, like open burning of tires, that release hazardous pollutants; (ii) ambient air quality: setting maximum allowable levels for key outdoor air pollutants; (iii) wood burner standards: requiring new wood burners in urban areas to meet design standards; and (iv) landfill emissions: mandating landfills with over 1 million tons of refuse to collect greenhouse gas emissions. • New Zealand follows EU emissions standards but also gives the option of compliance with US Federal or Japanese standards. Current emissions standards are Euro 5/V levels. Euro 6 and Euro VI emissions standards[50] are going to apply starting from 1 July 2027 and from 1 November 2024, respectively.
Nigeria	• National Environmental (Air Quality) Regulations,[51] 2014. S.I. no. 64/2014. • National Environmental Protection (Pollution Abatement in Industries and Facilities) Regulation, 1991 focuses on controlling pollution from industries and waste-generating facilities. • Nigeria is already importing 50 ppm diesel fuels (UNEP, 2021c). • Management of Solid and Hazardous Wastes Regulations, 1991 outlines a comprehensive list of hazardous wastes and regulates their management. • Since 2011, Euro 2 standards were adopted in Nigeria and 2015 was set as the date for enforcement of Euro 3 standards in the country (Cervigni et al., 2013). • Restrictions on used car importation include a 15-year age limit for vehicles.
Norway	• A regulation from 1997 introduced emission limits for PM_{10} for wood burning stoves sold in Norway. • Air quality legislation/programs:[52] The Pollution Control Act of 13 March 1981 to protect the outdoor environment against pollution and reduce existing pollution, and to reduce the quantity of waste and to promote better waste management. • National ambient air quality standards: As a party to the "Agreement on the European Economic Area" (EEA), Norway must also comply with EU Directives. The current standards are contained in the Clean Air for Europe Directive (EP & CEU, 2008) and the Fourth Daughter Directive (EP & CEU, 2004). These Directives also include rules on how Member States should monitor, assess, and manage ambient air quality. Norway has decided to tighten its limit values for particulate matters from 1 January 2016. Norway will thus have stricter limit values than the requirement from the EU Directives. • Norway has transposed the EU legislation on quality requirements of fuel, as such the sulfur content is regulated at below 10 ppm for both gasoline and diesel. • The EU has introduced common limit values for exhaust emissions to limit pollution. • The EU Industrial Emissions Directive (2010/75/EU) entered into force on 6 January 2011. The directive tightens emission limit values (ELVs) in certain industrial sectors across the EU. For combustion plants, NO_X, SO_2, and particulate matter levels were tightened and carbon monoxide limits were added for gas fired plants. It also introduced minimum standards for environmental inspections of industrial installations and sets out requirements for more frequent permit reviews through the cyclic review and application of Best Available Techniques conclusions. • Vehicle emission limit: Emissions standards for vehicles correspond to Euro 6 for light-duty vehicles, VI for heavy-duty vehicles. As a member of the Agreement on the European Economic Area, Norway is obliged to introduce EC Regulation No. 715/2007 and its implementing Regulation (EC) No. 692/2008. This Regulation sets tighter vehicle emission limits, known as Euro 5 and Euro 6.

48 Morocco's emissions legislation database is available at: https://www.emleg.com/legislation/view/morocco-general

49 New Zealand's Air Quality Policy Matrix is available at: https://wedocs.unep.org/bitstream/handle/20.500.11822/17069/New%20Zealand.pdf

50 New Zealand's emissions legislation database is available at: https://emleg.com/legislation/view/new-zealand-general

51 Federal Republic of Nigeria Official Gazette, vol. 101, no. 142/2014.

52 For more information on Norway's country-level policies that impact air quality, see the Norway Air Quality Policy Matrix at https://wedocs.unep.org/bitstream/handle/20.500.11822/17075/Norway.pdf

World region	Air pollution control policies, measures, standards and regulations
Pakistan	• Large power plants: Moderate particulate matter controls (for instance, single field electrostatic precipitators for existing plants, multifield electrostatic precipitators for new plants) and effective desulfurization of flue gases at modern large coal power stations. • Diesel generators: low sulfur diesel oil—stage 2 (0.045 percent sulfur) controls, shifting to gas-based generators (25 percent by 2030). • Households: Low sulfur coal, diesel, and furnace oil; introducing improved biomass cookstoves (goals set for different provinces, typically few percent of capacity by 2030); switch to cleaner cooking fuels (about 80 percent of urban households by 2030). • Restrictions on the open burning of Agriculture crop residue. • Industry: Particulate matter controls (cyclones and electrostatic precipitators) in industrial process sectors; less than 10 percent operated as zigzag kilns in 2021 and 50 percent by 2030. • Heavy-duty trucks and buses (diesel): gradual introduction of Euro V, goals set for 2030. • Light-duty vehicles (gasoline): gradual introduction of Euro 5, goals set for 2030. • Light-duty vehicles (diesel): gradual introduction of Euro 5, goals set for 2030. • Mopeds: gradual introduction of Stage 1 (4-stroke) controls. Goals are: 1/3 of by 2030 and about 15 percent complying with Stage 1 (2-stroke).
Peru	• Since January 1, 2003, all new light-duty vehicles in Peru have been required to meet either US or EU emission standards (Euro 2 or US Tier 0) and from 2007, must meet Euro 3 requirements. • New heavy-duty vehicles are required to meet Euro II from 2003 and Euro III from 2007.
Philippines	• All Philippine-registered ships in international trade must comply with the 0.50 percent mass by mass sulfur content limit by January 1, 2020, while those in domestic trade must meet the same limit by January 1, 2025 (MARINA, 2020). • Emission trading credits are allowed as part of compliance, excluding non-attainment areas. • Euro 4/IV standards[53] have been in place since 1 January 2016 for light-duty and heavy-duty vehicles, respectively. For motorcycles and mopeds, Level 2 (Euro 3) standards have been in place since September 2015. • The Solid Waste Management Act prohibits open burning, but it is still common; only 26 percent of local government units implement the Act. • The National Air Quality Policy, established under the Clean Air Act (1999), faces implementation challenges. • Used car importation is generally banned, with exceptions for certain trucks and buses.
Russia and EAEU	• Russian emission and fuel regulations are based on UN ECE regulations and EU standards, which apply to both manufactured and imported vehicles. Russia introduced mandatory Euro 2 in 2006 and increased the requirements—Euro 5 standards came into effect in 2014. • Since 2013, Russian emission regulations have been applicable to member states of the Eurasian Economic Union (EAEU, formerly Eurasian Customs Union), which includes Armenia, Belarus, Kazakhstan, the Kyrgyz Republic, and Russia. • Russian emission standards for light-duty vehicles and heavy-duty engines are outlined in Resolution No. 609: Special Technical Regulations on Requirements for Emissions of Hazardous (Polluting) Substances by Vehicles, first adopted in 2005, and its subsequent amendments. At the EAEU level, the regulations are outlined in the Technical Regulation "On the Safety of Wheeled Vehicles", adopted in 2011. • While Russia has adopted some EU emission standards for mobile nonroad engines (from 2017 requiring Stage III), progress has been delayed, as some of the EAEU countries have been slow in updating emission standards from Stage 0.
Rwanda	• Air quality standards and regulations proposed by the Rwanda Environment Management Authority[54] in 2014, leading to the implementation of a fully functional air quality regulation system. • Diesel sulfur content is capped at 50 ppm and leaded fuel has been phased out since 2005. Additionally, only brand-new motorcycles are allowed for importation.
Singapore	• Emission requirements are based on EU, Japanese, and US emission standards and test methods, which are incorporated in regulations by reference. Singapore emission regulations are part of the Environmental Protection and Management Act of 1 July 1999, with a number of later amendments. • For light-duty gasoline vehicles: Euro 1 (1994), Euro 2 (2001), Euro 4 (2014), Euro 6 Japan 2009 plus Euro 6 PN limit for GDI vehicles (2017). • For light-duty diesel: Euro 1 (1998), Euro 2 (2001), Euro 5 or Japan 2009 (2014), Euro 6 or Japan Euro 6 plus Euro 6 PN limit (2018). • For heavy duty diesel: Euro I (1998), Euro II (2001), Euro IV (2006), Euro V or Japan 2009 standard (2014), Euro VI or Japan 2009 plus Euro VI PN limit (2018). • For non-road diesel engines US Tier 1 or EU Stage I or Japan standards from 2000. • And from 2012 requirement to comply with US Tier 2 or EU Stage II or Japan Tier I (MOT).

53 The Republic of Philippines' emissions legislation is available at https://emleg.com/legislation/view/philippines-general

54 Rwanda Air Quality Policy Matrix is available at: https://wedocs.unep.org/bitstream/handle/20.500.11822/17090/Rwanda.pdf

World region	Air pollution control policies, measures, standards and regulations
South Korea	• The Korean government's "Comprehensive Plan on Fine Dust Management" aims to reduce $PM_{2.5}$ emissions by 35.8 percent by 2022,[55] leading to a decrease in annual $PM_{2.5}$ concentration from 25 µg/m³ to 17–18 µg/m³ and the number of poor air quality days from 64 to 40. • Introduce the "Dust Cap Regulation" targeting emission facilities in the Seoul Metropolitan Area and apply stricter permissible emissions levels to business facilities. • Strengthen control over emissions from coal-fired power plants and increase penetration rates of new renewable energy. • Mitigate fugitive dust from roads, root out illegal incinerations, and reduce emission sources of fine dust in urban and rural areas. • Apply tighter emission standards to diesel vehicles, expand restrictions of driving diesel vehicles, and encourage the use of eco-friendly cars. • Diesel and gasoline are limited to 10 ppm sulfur.[56] Limits on benzene and aromatics in gasoline are among the most stringent in the world and on par with Europe.
Switzerland	• Emission requirements from new highway engines, both light- and heavy-duty, are harmonized to accept the current EU regulations. • New engines for nonroad vehicles and machinery must meet the current EU emission standards for all regulated pollutants. • In addition, Switzerland adopted emission standards for nonroad engines used in construction that are more stringent than the European requirements. Diesel engines used in new construction machines must comply with a Swiss particle number emission limit. The particle number emission requirements ensures that all construction machines sold in Switzerland be fitted with diesel particulate filters. • Particulate filter retrofits are also required for in-use diesel engines used in construction projects.
Thailand	• Vehicle emission standards and testing procedures are based on EU regulations and are developed by the Thai Industrial Standards Institute, an agency within the Ministry of Industry, and the Pollution Control Department, an agency of the Ministry of Natural Resources and Environment. • For light-duty vehicles: Euro 1 (1994), Euro 2 (1999), Euro 3 (2006), Euro 4 (2012). • For heavy-duty engines: Euro I (1998), Euro II (2000), Euro III (2008), Euro IV (2012).
Türkiye	• For light-duty vehicles: Euro 1 for diesel from 2001, Euro 3 for gasoline from 2001, Euro 4 for gasoline and diesel vehicles from 2008 and from 2010 Euro 5. • For heavy-duty vehicles: Euro I effective in 2001, Euro IV from 2007, Euro V from 2011, and Euro VI from 2015. • Fuel quality: 50 ppm sulfur in diesel commercial vehicles and 1,000 ppm sulfur in diesel for agricultural tractors.
United Kingdom	• Air pollution control policies in the UK closely follow EU regulations. The UK's Environment Act of 2021 further strengthens its commitment to air quality improvement, incorporating many of the EU's environmental principles and objectives.
United States	• The US Clean Air Act establishes the primary framework for national, state, tribal, and local air quality protection. It mandates the US Environmental Protection Agency (EPA) to set National Ambient Air Quality Standards (NAAQS) for public health and welfare. Enacted in 1970 and amended in 1990, the Clean Air Act regulates pollutants, emissions, acid rain, ozone protection, and assigns oversight to the EPA with state enforcement. Federal courts and citizens can challenge EPA actions. • All new industrial plants or major additions to existing plants, regardless of size or location, need to adhere to New Source Performance Standards.[57] • The most recent US emission standards for light-duty vehicles are the Tier 4 standards, following earlier Tier 1, Tier 2, and Tier 3 regulations. These standards, developed under Clean Air Act Amendments, were phased in progressively: Tier 1: adopted in 1991, phased in from 1994 to 1997; Tier 2: adopted in 1999, phased in from 2004 to 2009; Tier 3: finalized in 2014, phased in from 2017 to 2025; Tier 4: adopted in 2024, to be phased in from 2027 to 2033. • Several states have opted for California's standards under Clean Air Act (Section 177) to meet their air quality goals, including: Advanced Clean Cars II (2026) including Low-Emission Vehicle (LEV) IV criteria pollutant standards and zero emission vehicle requirements for model years 2026 and later; LEV Criteria Pollutant Standards (1992); LEV Greenhouse Gas Standards (2009) and Zero Emission Vehicle Standards (1990). • Federal emission standards for engines and vehicles are set by the US Environmental Protection Agency under the authority of the Clean Air Act. • CAFE standards: fuel economy for new light-duty vehicles. • The California Air Resources Board's low NO_X emission standards can set its own, often stricter, emission regulations for California. • Open burning rules and regulations are enforced by insurance fines and penalties.

55 For more information on the South Korean Ministry of Environment's strategies to address air pollution, see https://www.me.go.kr/eng/web/index.do?menuId=464

56 South Korea's fuel standards are available at https://www.transportpolicy.net/standard/south-korea-fuels-diesel-and-gasoline/

57 The Nonmetallic Mineral Processing: New Source Performance Standards are available at https://www.epa.gov/stationary-sources-air-pollution/nonmetallic-mineral-processing-new-source-performance-standards

World region	Air pollution control policies, measures, standards and regulations
Vietnam	• Emission standards for thermal power industry (MoNRE, 2009a). • Industrial emission standards for dust and inorganic substances (MoNRE, 2009b). • National Technical Regulation on emissions for oil refinery industry (MoNRE, 2010). • National Technical Regulation on industrial emissions for chemical fertilizer production (MoNRE, 2009c). • National Technical Regulation on industrial emissions for cement production (MoNRE, 2009d). • National Technical Regulation on emissions for steel industry (MoNRE, 2013). • Euro 2/II for light-duty and heavy-duty vehicles, gasoline and diesel until 2018. • Euro 4/IV since 2018 and Euro 5/V from 2022/23 onwards. • Passenger vehicles in Vietnam[58] must comply with Euro 5(V) emissions standards, while diesel and other heavy-duty vehicles must comply with Euro 4(IV). 2 and 3 wheeled motorcycles and other vehicles are required to comply with either Euro 2(II) or 3(III).
Western Balkans	• Western Balkan countries (Albania, Bosnia Herzegovina, North Macedonia, Kosovo, Serbia, and Montenegro) have been developing legislation to align with the EU law for both stationary (namely, Large Combustion Directive, Industrial Emission Directive) and mobile (Euro standards for road and non-road) vehicles. Furthermore, the countries in the region are also adopting the Technical Annexes to the UNECE Gothenburg Protocol. Detailed information about the current policies has been compiled and documented in the TFETI report (Allemand and Sirina-Leboine, 2023).

Source: IIASA GAINS model

Table B.3.
Examples of cost effective energy and climate policy and AQM measures to achieve the Clean Air Targets

The energy and Noclimate policy measures considered in the analysis reflecting the Sustainable Development Scenario of the 2021 IEA World Energy Outlook, as well as key measures emerging from the GAINS analysis as cost-effective for achieving the Clean Air Targets in the 15 world regions.

Column A contains examples of the key energy and climate policies and measures assumed in the "additional climate policies only" scenario. Column B contains sample of the measures reflected in the "additional AQM policies only" scenario. The "Integrated Policies scenario" draws from Columns A and B. The policies and measures in Columns A and B are not exhaustive due to space constraints.

Source sectors in which measures for exposure reduction are considered	A. Key energy and climate policies and measures for the various emission source sectors reflecting the analyses for the Sustainable Development Scenario of the 2021 IEA World Energy Outlook	B. Examples of cost-effective air pollution control measures for the various emission source sectors
Cross-cutting	• Phase out fossil fuel subsidies • Staggered introduction of CO_2 prices.	
Power generation	• Increased deployment of renewables • Lifetime extension of nuclear power plants and some new builds where applicable and with public acceptance • Efficiency and emission standards that prevent the refurbishment	• Application of high efficiency flue gas cleaning technology, including high efficiency dust removal (electrostatic precipitators), flue gas desulfurization, and selective catalytic reduction.

58 More information on Vietnam's Euro 5(V) emissions standards for passenger vehicles is available at https://www.transportpolicy.net/region/asia/vietnam/

Source sectors in which measures for exposure reduction are considered	A. Key energy and climate policies and measures for the various emission source sectors reflecting the analyses for the Sustainable Development Scenario of the 2021 IEA World Energy Outlook	B. Examples of cost-effective air pollution control measures for the various emission source sectors
Industry	• Policies to support circular economies through increased recycling of aluminum, steel, paper and plastics, and materials efficiency strategies • Enhanced minimum energy performance standards, in particular for electric motors; incentives for introducing variable speed drives in variable load systems; and implementing system-wide efficiency measures • Mandatory energy management systems or energy audits.	—
Industrial combustion	—	• Stringent emission standards for industrial facilities above 50 MWth using solid fuels • High efficiency flue gas cleaning in industrial boilers (especially for solid fuels) including high efficiency dust removal (electrostatic precipitators), low-NO_X burners, flue gas desulfurization, and selective catalytic reduction.
Industrial processes	—	• Improvements in process technology as well as more efficient capture and removal of process and fugitive emissions from industrial processes.
Household solid fuel use	• Universal access to electricity and clean cooking.	• Clean alternatives for traditional cooking with biomass, such as switch to liquefied petroleum gas or piped natural gas stoves, or electric induction cookers • Accelerated replacement of traditional biomass cook stoves with new more efficient stoves (including fan-assisted stoves) • Accelerated introduction of new heating stoves and boilers with higher combustion efficiencies and basic pollution controls • Switch to biomass pellet stoves and boilers.
Other residential	• Phase out the least efficient appliances, light bulbs, and heating/cooling equipment • Mandatory energy performance standards for all appliances and space cooling equipment • Mandatory energy conservation building codes, including net zero emission for new buildings • Increased support for energy efficiency and CO_2 emissions reduction measures in existing buildings, including retrofits, heat pumps, direct use of solar thermal, and geothermal energy in some countries • Digitalization of electricity demand in the building sector to increase demand-side response potential through increased flexibility and control of end-use devices.	• Accelerated introduction of modern boilers with higher combustion efficiency and use of low-sulfur fuel • Switch to biomass pellet boilers.
Heavy-duty vehicles	• New heavy-duty vehicles that are about 20 percent more efficient than in the current baseline.	• Strict legislation requiring more frequent and enforced vehicle inspection and maintenance of vehicles with mandatory elimination or repair of high-emitting vehicles • More stringent emission limit values for vehicles (the further potential is estimated assuming the immediate introduction of Euro VI/6 equivalent emission standards for new vehicles).
Other transport (especially light-duty vehicles) and road dust	• On-road vehicle stock emissions intensity limited to 50 g CO_2/km in countries with net-zero pledges and 130 μg/m^3 elsewhere by 2040. This implies an aggressive introduction of electric vehicles • Phase out two-stroke engines.	• Strict legislation requiring more frequent and enforced vehicle inspection and maintenance of vehicles with mandatory elimination or repair of high-emitting vehicles • More stringent emission limit values for vehicles (the further potential is estimated assuming an immediate introduction of Euro VI/6 equivalent emission standards for new vehicles) • Paving and regular road cleaning.

Source sectors in which measures for exposure reduction are considered	A. Key energy and climate policies and measures for the various emission source sectors reflecting the analyses for the Sustainable Development Scenario of the 2021 IEA World Energy Outlook	B. Examples of cost-effective air pollution control measures for the various emission source sectors
Municipal solid waste	• Policies to support circular economies through increased recycling of aluminum, steel, paper, and plastics, as well as materials efficiency strategies.	• Policies to support circular economies through increased recycling of aluminum, steel, paper, and plastics, as well as materials efficiency strategies • Solid municipal waste management reducing amounts of trash burning and introducing efficient waste collection and recycling schemes.
Agriculture	—	• For large industrial farms: Ammonia emissions control for livestock production in large industrial farms (covered storage of manure, efficient manure application on land, new animal houses built according to low-emission housing standards) • Efficient application of mineral nitrogen fertilizers, including improved application of urea (proper timing and dose), and/or potentially the use of urease inhibitors, triggered through proper incentive programs • No measures are assumed for small subsistence farms.
Crop residue burning	—	• Introduction and efficient enforcement of bans on open burning of agricultural residues • Energetic use of crop residue or conversion of crop residue to pellets.
Forest and peatland fires	• Prevention through appropriate management approaches.	—
Other	—	• Reduced routine flaring during fuel extraction and processing • Reduced fugitive dust emissions from mining industry.

The analysis presented in this report does not include prevention of forest and peatland fires through appropriate management policies. Also, large-scale measures to reduce desertification are excluded from the analysis for 2040. Similarly, dietary changes that reduce meat consumption (a shift to less meat protein in diets resulting in lower livestock numbers and also lower mineral fertilizer use) are not considered here.

Table B.4.
Diffuse and small-scale sources of pollution and corresponding control measures

Source sectors	Key air pollution control measures for the various emission source sectors (key measures that emerge from the GAINS analysis as cost-effective for achieving the Clean Air Targets in the 15 world regions)
Household solid fuel use	• Clean alternatives for traditional cooking, including liquefied petroleum gas stoves and higher efficiency solid fuel stoves, such as fan stoves. • For heating: new stoves or a switch to pellets.
Other residential	• Modern boilers, low-nitrogen-oxide burners, use of low-sulfur fuel, pellets.
Heavy-duty vehicles	• Introducing ever more stringent emission limit values for vehicles. Further potential is estimated assuming the immediate introduction of legislation requiring new vehicles (road and non-road) to meet Euro VI/6-equivalent emission standards. • Introducing stricter legislation requiring more frequent and enforced vehicle inspection and maintenance of vehicles that will enable early recognition and elimination/repair of high-emitting vehicles.

Source sectors	Key air pollution control measures for the various emission source sectors (key measures that emerge from the GAINS analysis as cost-effective for achieving the Clean Air Targets in the 15 world regions)
Other transport including road dust	• Introducing ever more stringent emission limit values for vehicles. Further potential is estimated assuming the immediate introduction of legislation requiring new vehicles (road and non-road) to meet Euro VI/6-equivalent emission standards. • Introducing stricter legislation requiring more frequent and enforced vehicle inspection and maintenance of vehicles that will enable early recognition and elimination/repair of high-emitting vehicles. • Paving roads and regular road cleaning.
Municipal solid waste	• Primarily addressing solid municipal waste management reducing amounts of trash burning and introducing efficient waste collection and recycling schemes. Measures addressing industrial waste and domestic water waste will bring methane mitigation benefits.
Agriculture	• Control of ammonia emissions from livestock production and mineral nitrogen fertilizer application. Livestock measures include requirements to construct new low-emission housing, covered stores for manure and efficiently applying manure on land. For mineral fertilizers, emissions from urea use are addressed either by replacing urea with ammonium nitrate or improving urea (proper timing and dose) and potentially urease inhibitor application.
Crop residue burning	• Introduction and efficient enforcement of bans on open burning of agricultural residues.

APPENDIX C. DEVELOPMENT FINANCE INSTITUTION INTERVENTIONS

Select Institutions	Examples	Modality
World Bank	Air Quality Management Program India: State air quality action plans; the regional Airshed Action Plan for Indo-Gangetic Plains; and assistance to West Bengal Transport Corporation for electric vehicle transition Pipeline projects include the Uttar Pradesh Clean Air Management Program (US$350 million) and the Haryana Clean Air and Sustainable Development Program (US$300 million) Multiple initiatives from 2018 and support levels	Multiyear technical assistance
	Energy Sector Management Assistance Program (ESMAP) across the globe Clean Cooking Fund to provide access to 100 million people by 2025. (2019; US$440 million)	Technical assistance and investments
	Kyrgyz Republic Air Quality Improvement Project: International Development Association credit for air quality improvement (2023; US$ 50 million)	Concessional lending and revolving fund
	Jing-Jin-Ji program: China to reduce air pollution and carbon emissions (2016; US$500 million)	Results-based lending
	Ulaanbaatar Clean Air Project, Mongolia (2012; US$27 million)	Concessional lending and zero-interest credit
	Bangladesh Environmental Sustainability and Transformation (BEST) (2022; US$250 million)	Concessional financing and a credit guarantee fund
	Greater Cairo Air Pollution Management and Climate Change Project: air quality management, solid waste management, and e-mobility (2020; US$200 million)	Investment project financing
	Türkiye Industrial Emissions Reduction Project (2024; US$ 417 million)	Financial institution loan
Asian Development Bank	Ulaanbaatar Air Quality Improvement Program Mongolia (2018; US$290 million)	Policy-based lending
	Beijing-Tianjin-Hebei program China for clean rural household energy (2019; US$300 million)	Results-based lending

Select Institutions	Examples	Modality
	Bangladesh, Mongolia, Pakistan, Philippines, and Vietnam: knowledge sharing and city-level clean air action plans (different years and support quantum)	Regional technical assistance
African Development Bank	Clean cooking initiatives in Africa: committed to allocating up to 20 percent of annual energy lending for clean cooking solutions. Invested in SPARK+ Africa Fund for clean cooking (2020; African Development Bank US$5 million, European Commission €10 million)	Investment financing
	Ghana, Kenya, and Cameroon: funded by FAPA and JICA for scaling up clean cooking industry (2017; ~ US$1 million)	Multicountry technical assistance
Korean institutions	Mongolia and ASEAN countries: feasibility studies, master plans, and regional partnerships funded by EDCF, KEITI, and KOICA. (2019; various support levels)	Technical assistance and investment financing
European Investment Bank	Cleaner Transport Facility in EU: supporting alternative fuels and cleaner transport technologies) (2017; €187 million)	Grants and loans
	East Africa Clean Cooking Expansion in Kenya, Tanzania, other African countries (2023; US$ 15 million)	Investment financing
	Energy-efficient buildings in Spain (2024; €300 million)	Covered bonds
Agence Française de Développement	Egyptian Pollution Abatement Project for industrial pollution reduction (2007; €50 million)	Sovereign concessional loan, credit line, investment bonus, and technical assistance
	Public transport development in Lima, Peru: developing an efficient and sustainable public transport system. (2015; €120 million)	Sovereign loan
USAID	Clean Air Catalyst: Global, starting in India and Indonesia combating air pollution (2021; US$20 million)	Technical assistance
	Nepal: multisectoral approach to reduce air pollution in Kathmandu Valley (2021; US$13 million)	Investment financing
	Vietnam: addressing pollution challenges in targeted areas (2021; US$ 11 million)	Grants and investments
JICA	India: mass transit projects across multiple Indian cities and partnering with ADB through the Japan Fund for the Joint Crediting Mechanism for low-carbon technology adoption. (various years from 1997 and support levels)	Investment financing, concessional loans, and technical assistance

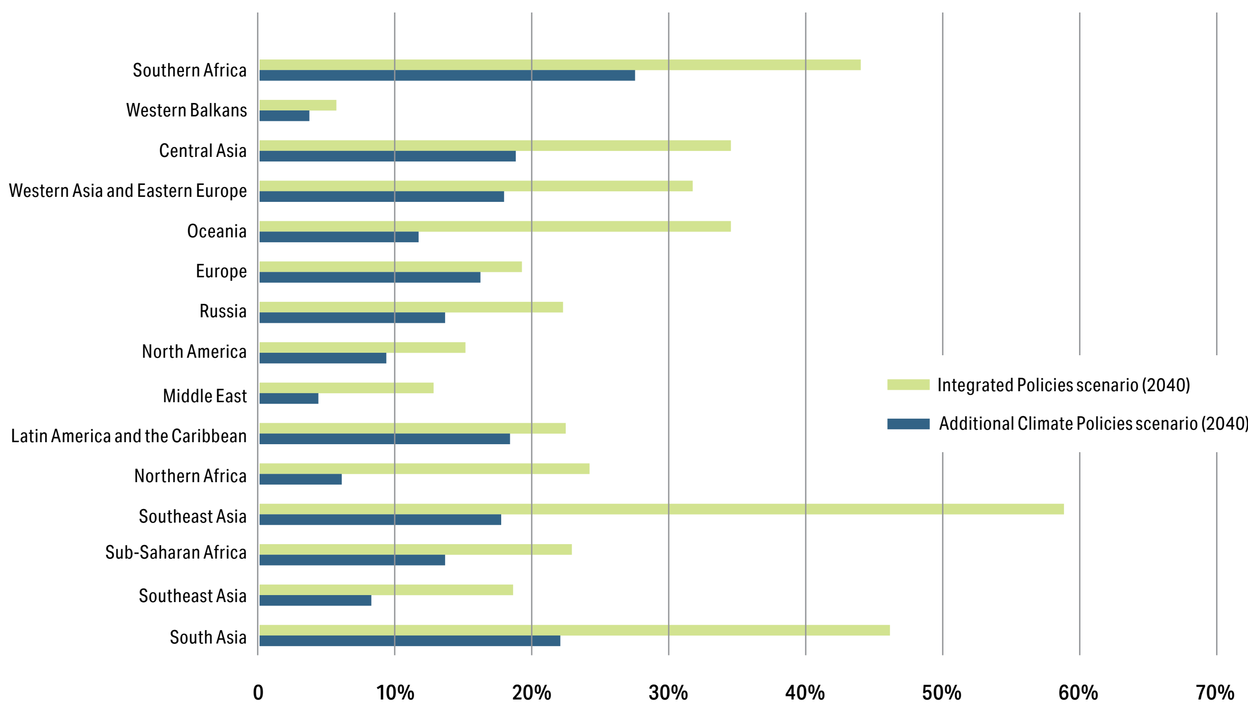
APPENDIX D. METHODOLOGY FOR QUANTIFYING AIR POLLUTION MORTALITY AND ASSOCIATED ECONOMIC DAMAGES

This section is based on the results from IIASA modeling, which was an input for this report. The modeling provided numbers for exposure, which were applied using a methodology based on Burnett et al. (2018) to come up with the number of deaths due to air pollution. We chose this approach over others, such as the Global Burden of Disease (GBD) 2021 study, because it focuses exclusively on ambient air pollution exposure. This focus aligns with our study's aim to specifically evaluate policy impacts on ambient air pollution. While these policies would also reduce household pollution, this analysis does not directly estimate those effects. Following Burnett et al. (2018), we estimated air pollution-attributable mortality for ischemic heart disease, stroke, chronic obstructive pulmonary disease, lower respiratory infections and other non-communicable diseases.

Compared to the Stated Policies scenario, both the Additional Climate Policies Only and Integrated Policies scenarios are projected to significantly reduce global mortality attributable to ambient air pollution by 2040. Our results indicate that, under the Stated Policies scenario, mortality attributable to ambient air pollution is projected to increase from 5.7 million deaths in 2020 to 6.2 million deaths in 2040. This rise reflects anticipated population growth from nearly 8 billion in 2020 to 8.9 billion in 2040, suggesting that while absolute mortality numbers increase, air pollution-attributable mortality rates remain relatively stable. The Additional Climate Policies Only and Integrated Policies scenarios project 5.3 and 4.1 million deaths in 2040, respectively, with most of the deaths caused by lower respiratory diseases, stroke, lung cancer, chronic obstructive pulmonary disease, and ischemic heart disease. These figures represent a 16 percent reduction in mortality for the Additional Climate Policies Only scenario and a 34 percent reduction for the Integrated Policies scenario in 2040 compared to the Stated Policies scenario, as illustrated in Figure 1.9.

The impacts of the policy scenarios vary significantly across regions, reflecting the differing levels of air pollution reduction in each area, as illustrated in Figure D1. The largest reductions in ambient air pollution-attributable mortality are anticipated in Southeast Asia, South Asia, and Southern Africa—regions that together account for 66 percent of the global mortality reduction achieved under the Integrated Policies scenario, as these regions also experience the most substantial decreases in $PM_{2.5}$ pollution. In contrast, the smallest reductions in mortality under the Integrated Policies scenario compared to the Stated Policies scenario, (that is, reductions below 6 percent), are projected for the Western Balkans, with reductions of under 20 percent also observed in the Middle East, Southeast Asia, Europe, and North America.

Figure D1. Reduction in ambient air pollution-attributable mortality compared to the Stated Policies scenario in 2040



Source: Original calculations based on Burnett et al. (2018).

To demonstrate the economic benefits of reducing ambient air pollution, we estimated the potential economic value of averted air pollution-attributed mortality across various policy scenarios. To do so, we used the value of statistical life (VSL) as determined by the Organisation for Economic Co-operation and Development (OECD) and followed the methodology of Merk et al. (2012) and Narain and Sall (2016). Using this approach, the value of averted mortality (in 2021 terms) for the Additional Climate Policies Only scenario ranged from US$0.9 trillion to US$1.2 trillion—or 0.8 percent to 1 percent if global GDP in 2040. The value of averted mortality under the Integrated Policies scenario ranged from US$1.9 trillion to US$2.4 trillion—or 1.7 percent to 2.1 percent of global GDP in 2040.

METHODOLOGY

Estimating country-level $PM_{2.5}$ concentrations

We estimated country-level $PM_{2.5}$ concentrations based on regional values by using 2020 baseline data from the GBD 2021 study (IHME, 2021). First, we calculated the population-weighted average of $PM_{2.5}$ concentrations for each region using the GBD 2021 data. Next, we determined an adjustment factor for each region by dividing the $PM_{2.5}$ concentration values for each of the modeled concentrations (one for 2020 and three for 2040 under different scenarios) by the 2020 population-weighted regional average (Equation 1). These adjustment factors represent the proportional differences between the modeled $PM_{2.5}$ concentrations and the GBD 2021 baseline for each region. Finally, to align country-level $PM_{2.5}$ estimates with the modeled regional averages for all scenarios in 2040, we applied these regional adjustment factors to each country's baseline $PM_{2.5}$ concentration from the GBD 2021 data (Equation 2). This method ensures that country-level contributions to regional $PM_{2.5}$ average concentrations are consistent with the broader regional trends projected under each scenario.

$$AF_{region,scenario} = \frac{conc_{scenario,region}}{GBD\ conc_{region}} \qquad (1)$$

$$conc_{scenario,country} = AF_{region,scenario} * GBD\ conc_{country} \qquad (2)$$

Mortality estimation using Burnett et al. (2018) methodology

Unlike the integrated exposure-response function, which combines relative risk data from studies on ambient air pollution, active and secondhand smoking, and household solid fuel cooking— and requires strong assumptions about equivalent exposure and toxicity across these sources— the methodology developed by Burnett et al. (2018) constructs a hazard-ratio function using only cohort studies of outdoor ambient air pollution. Their approach, known as the Global Exposure Mortality Model (GEMM), uses data from 41 cohorts across 16 countries, including a cohort of Chinese men, which further extends the $PM_{2.5}$ level coverage. Equation 3 shows the functional form of GEMM, and the parameters estimated are presented in Table D1.

$$GEMM(z) = \begin{cases} \exp\left\{ \dfrac{0 * \ln\left(\frac{z}{a}+1\right)}{1+\exp\left\{-\frac{(z-\mu)}{v}\right\}} \right\} & for\ z > 0 \\ 1 & for\ z \leq 0 \end{cases} \qquad (3)$$

Where $z = \max(0, PM_{2.5} - 2.4)$. The value 2.4 corresponds to a counterfactual concentration of $PM_{2.5}$, corresponding to the lowest concentration observed among the 41 cohorts. Below this concentration, no change in the hazard ratio was assumed. Figure D2 shows the hazard ratio predictions of the GEMM model for persons between 60 and 64 years of age. Since annual baseline mortality rates are small, hazard ratio functions can be interpreted as relative risk.

Table D.1.
Estimated GEMM function parameters

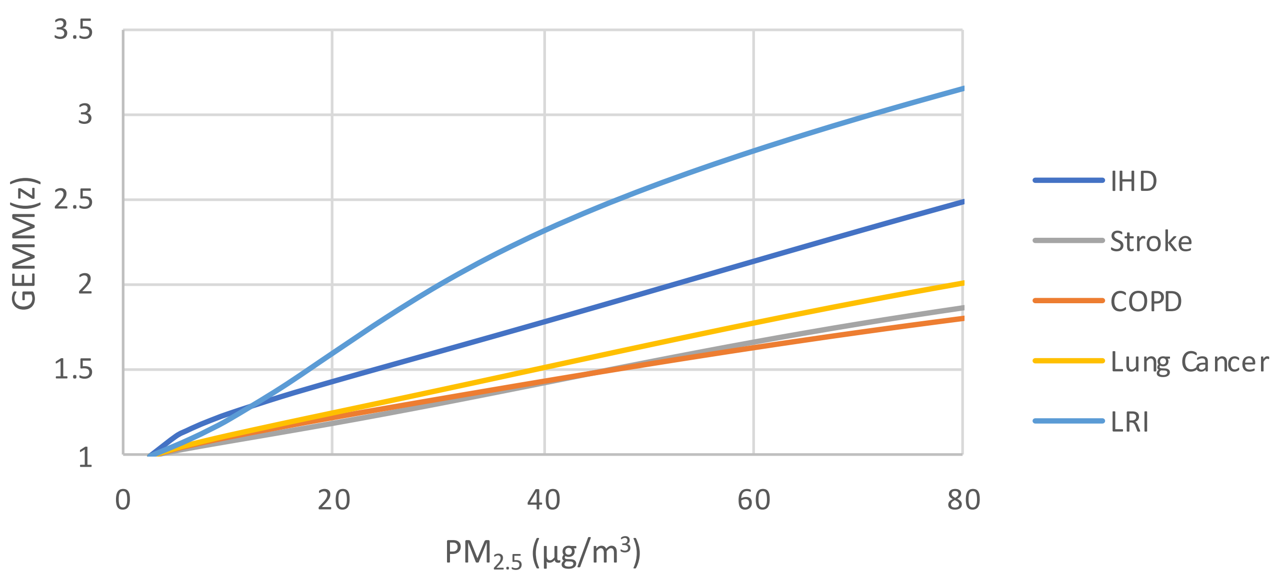
Cause of death	Range (years)	With Chinese Male Cohort				
		θ	standard error θ	α	μ	v
Non-communicable diseases and lower respiratory infections	>25	0.143	0.01807	1.6	15.5	36.8
	27.5	0.1585	0.01477	1.6	15.5	36.8
	32.5	0.1577	0.0147	1.6	15.5	36.8
	37.5	0.157	0.01463	1.6	15.5	36.8
	42.5	0.1558	0.0145	1.6	15.5	36.8
	47.5	0.1532	0.01425	1.6	15.5	36.8
	52.5	0.1499	0.01394	1.6	15.5	36.8
	57.5	0.1462	0.01361	1.6	15.5	36.8
	62.5	0.1421	0.01325	1.6	15.5	36.8
	67.5	0.1374	0.01284	1.6	15.5	36.8
	72.5	0.1319	0.01234	1.6	15.5	36.8
	77.5	0.1253	0.01174	1.6	15.5	36.8
	85	0.1141	0.01071	1.6	15.5	36.8
Ischemic heart disease	>25	0.2969	0.01787	1.9	12	40.2
	27.5	0.507	0.02458	1.9	12	40.2
	32.5	0.4762	0.02309	1.9	12	40.2
	37.5	0.4455	0.0216	1.9	12	40.2
	42.5	0.4148	0.02011	1.9	12	40.2
	47.5	0.3841	0.01862	1.9	12	40.2
	52.5	0.3533	0.01713	1.9	12	40.2
	57.5	0.3226	0.01564	1.9	12	40.2
	62.5	0.2919	0.01415	1.9	12	40.2
	67.5	0.2612	0.01266	1.9	12	40.2
	72.5	0.2304	0.01117	1.9	12	40.2
	77.5	0.1997	0.00968	1.9	12	40.2
	85	0.1536	0.00745	1.9	12	40.2
Stroke	>25	0.272	0.07697	6.2	16.7	23.7
	27.5	0.4513	0.11919	6.2	16.7	23.7
	32.5	0.424	0.11197	6.2	16.7	23.7
	37.5	0.3966	0.10475	6.2	16.7	23.7
	42.5	0.3693	0.09752	6.2	16.7	23.7
	47.5	0.3419	0.0903	6.2	16.7	23.7
	52.5	0.3146	0.08307	6.2	16.7	23.7
	57.5	0.2872	0.07585	6.2	16.7	23.7
	62.5	0.2598	0.06863	6.2	16.7	23.7
	67.5	0.2325	0.0619	6.2	16.7	23.7
	72.5	0.2051	0.05418	6.2	16.7	23.7
	77.5	0.1778	0.04695	6.2	16.7	23.7
	85	0.1368	0.03611	6.2	16.7	23.7

Cause of death	Range (years)	With Chinese Male Cohort				
		θ	standard error θ	α	μ	v
Chronic obstructive pulmonary disease	>25	0.251	0.06762	6.5	2.5	32
Lung cancer	>25	0.2942	0.06147	6.2	9.3	29.8
Lower respiratory infections	>25	0.4468	0.11735	6.4	5.7	8.4

Source: Burnett et al. 2018.

Burnett et al. (2018) presents parameter estimations with and without a Chinese male cohort. The results with the Chinese cohort were used in this analysis as they are exposed to the highest $PM_{2.5}$ concentrations observed for some of the considered regions.

Figure D2. GEMM hazard ratio predictions, group of persons aged 60 to 64



Note: Ischemic heart disease = IHD; chronic obstructive pulmonary disease = COPD; and lower respiratory infection = LRI.

Source: Original calculations based on Burnett et al. 2018.

Main assumptions and data sources

We calculated baseline health outcomes by utilizing population projection data from the United Nations and incidence rates from the GBD 2021 study. We sourced $PM_{2.5}$ concentration data from WHO to determine the slope and intercepts of relative risk functions for rural and urban areas. We assumed that the incidence rates of diseases remain constant throughout the period of analysis, and we used the lower and upper values of the incidence rates to estimate the ranges of mortality in all of the scenarios. Due to the lack of specific data for Kosovo, the baseline incidence rates were assumed to be equivalent to those of Serbia.

Mortality burden valuation

To estimate the economic value of averted air pollution-attributable mortality, we used the value of statistical life (VSL) as determined by the OECD and followed the methodology of Merk et al. (2012) and Narain and Sall (2016), according to the equation:

$$VSL_C = VSL_{OECD,2005} * \left(\frac{Y_C}{Y_{OECD,2005}} \right)^b * \ (1 + \%\Delta P + \%\Delta Y)^b$$

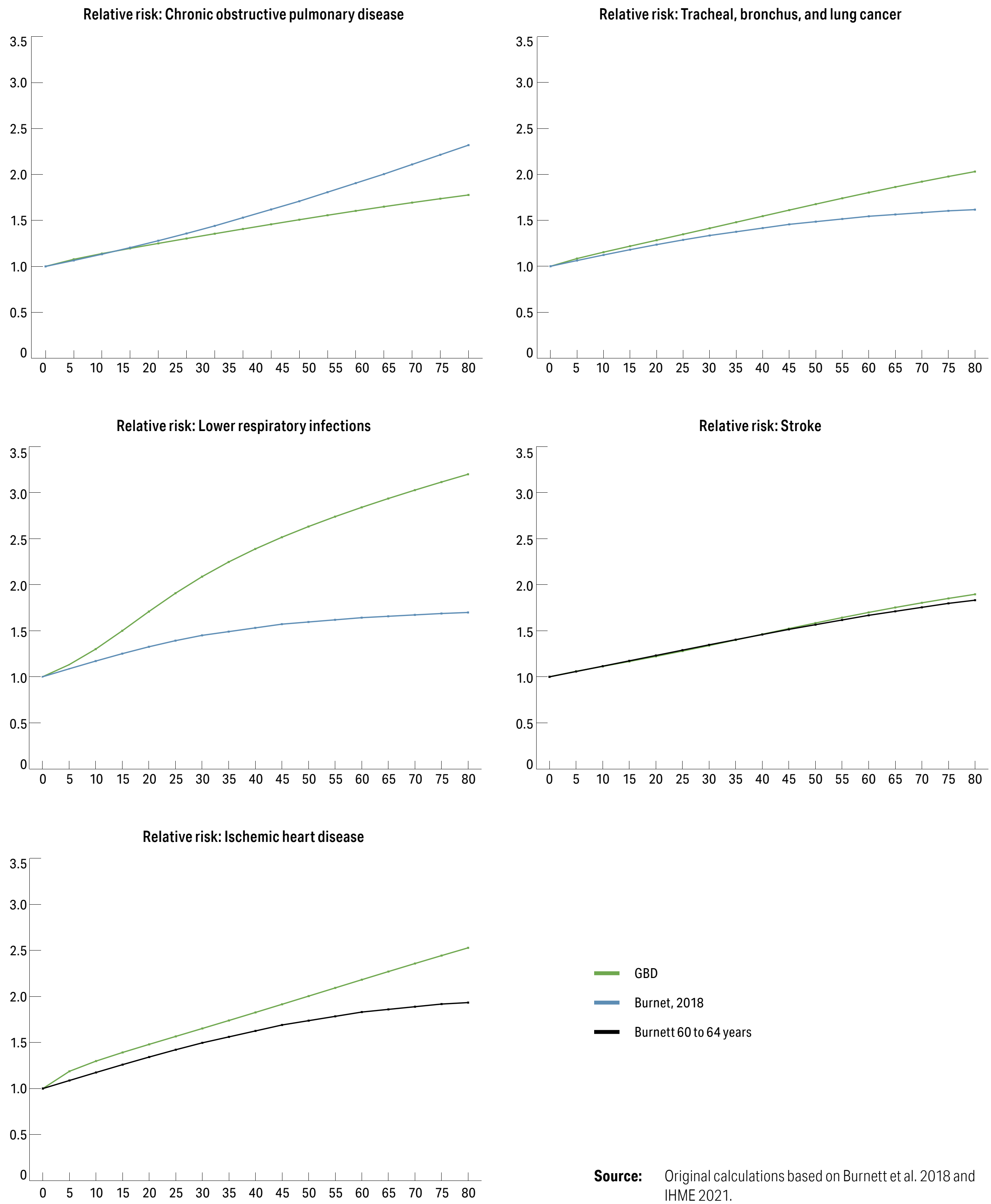
$VSL_{OECD,2005}$	Median VSL in OECD countries in 2005, in 2005 US$ purchasing power parity
Y	GDP per capita in PPP
b	Income elasticity for VSL in country c
$\%\Delta Y$	Income growth after 2005
$\%\Delta P$	Inflation according to consumer price index

The income elasticity (b) was determined through linear interpolation, ranging from 0.8 to 1.2, based on the GDP value of the respective country.

Comparison with Global Burden of Disease 2021 relative risk values

When comparing values of ambient air pollution-attributable mortality, it is worth noting that, in addition to the six diseases specified in the GBD 2021 methodology, Burnett et al. (2018) also consider other non-communicable diseases in their analysis. However, the available hazard ratios apply to age groups in five-year intervals starting only from age 25 and above. Figure D3 presents a comparison from the relative risk under Burnett et al. (2018) and the integrated exposure-response function from the GBD 2021 study.

Figure D3.
Comparison between Burnett et al. (2018) and GBD 2021 relative risk values



Source: Original calculations based on Burnett et al. 2018 and IHME 2021.

APPENDIX E. HIGHLIGHTS OF EXPOSURE UNDER DIFFERENT POLICY SCENARIOS AND KEY PRIORITY REDUCTION SECTORS UNDER THE INTEGRATED SCENARIO, BY REGION

	Population-weighted $PM_{2.5}$ exposure in region, followed by top five key emission source categories contributing to population-weighted $PM_{2.5}$ exposure, 2020	Population-weighted $PM_{2.5}$ exposure in region, followed by top five key emission source categories contributing to population-weighted $PM_{2.5}$ exposure, Stated Policies scenario	Population-weighted $PPM_{2.5}$ exposure in region, followed by top five key emission source categories contributing to population-weighted $PM_{2.5}$ exposure, Integrated Policies scenario	Key priority reduction sectors under the integrated scenario to halve the number of people exposed to levels above 25 μg/m^3 by 2040
Sub-Saharan Africa	**28 μg/m^3:** Desert dust (68%) Residential (19%) Other (4%) Agriculture (3%) Power and industry (3%)	**30 μg/m^3:** Desert dust (62%) Residential (21%) Power and industry (4%) Transportation (4%) Agriculture (4%) Other (4%)	**22 μg/m^3:** Desert dust (86%) Other (4%) Transportation (3%) Power and industry (2%) Residential (2%)	• Measures in the residential sector largely to address the use of solid biomass in households for cooking • Ending the open burning of agricultural residue
South Asia	**46 μg/m^3:** Residential (30%) Power and industry (22%) Desert dust (16%) Agriculture (12%) Transportation (10%)	**48 μg/m^3:** Power and industry (25%) Residential (21%) Desert dust (16%) Transportation (14%) Agriculture (12%)	**22 μg/m^3:** Desert dust (35%) Power and industry (17%) Agriculture (15%) Municipal solid waste (11%), Transportation (10%)	• Residential • Transportation • Crop residue burning for episodic events
Northern Africa	**34 μg/m^3:** Desert dust (65%) Power and industry (11%) Transportation (11%) Agriculture (5%) Residential (3%)	**37 μg/m^3:** Desert dust (59%)Transportation (16%) Power and industry (11%) Agriculture (6%) Residential (3%) Municipal solid waste (3%)	**26 μg/m^3:** Desert dust (84%) Transportation (4%) Agriculture (3%) Other (3%) Power and industry (2%) Municipal solid waste (2%)	• Transportation, further controls of vehicle emissions
Central Asia	**25 μg/m^3:** Desert dust (46%) Residential (18%) Power and industry (14%) Transportation (9%) Agriculture (8%)	**28 μg/m^3:** Desert dust (42% Transportation (17%) Power and industry (13%) Residential (13%) Agriculture (8%)	**18 μg/m^3:** Desert dust (66%) Transportation (11%) Agriculture (9%) Municipal solid waste (8%) Power and industry (3%)	• Transportation • Residential
Southeast Asia	**15 μg/m^3**: Transportation (25%) Power and industry (20%) Residential (19%) Agriculture (16%) Municipal solid waste (13%)	**19 μg/m^3:** Transportation (31%) Power and industry (21%) Agriculture (16%) Municipal solid waste (16%) Residential (11%)	**8 μg/m^3:** Transportation (30%) Municipal solid waste (27%) Power and industry (17%) Agriculture (16%) Other (14%)	• Transportation • Ending the open burning of agricultural residue • Enhanced wildfire management for episodic events
Southern Africa	**12 μg/m^3:** Residential (29%) Desert dust (25%) Other (15%) Power and industry (14%) Agriculture (9%)	**12 μg/m^3:** Residential (27%) Desert dust (26%) Other (13%) Agriculture (12%) Power and industry (10%)	**6 μg/m^3:** Desert dust (51%) Other (19%) Transportation (9%) Power and industry (7%) Agriculture (6%)	• Ending the open burning of agricultural residue • Measures in the residential sector largely to address the use of solid biomass in households for cooking

The priority sectors are based on the analysis. Priority sectors may differ in individual countries and airsheds. Analysis, consultations, and prioritization sequencing of measures will be required to determine priorities at individual airshed levels.

	Population-weighted $PM_{2.5}$ exposure in region, followed by top five key emission source categories contributing to population-weighted $PM_{2.5}$ exposure, 2020	**Population-weighted $PM_{2.5}$ exposure in region, followed by top five key emission source categories contributing to population-weighted $PM_{2.5}$ exposure, Stated Policies scenario**	**Population-weighted $PPM_{2.5}$ exposure in region, followed by top five key emission source categories contributing to population-weighted $PM_{2.5}$ exposure, Integrated Policies scenario**	**Key priority reduction sectors under the integrated scenario to halve the number of people exposed to levels above 25 µg/m³ by 2040**
Western Balkans	**25 µg/m³:** Residential (70%) Power and industry (8%) Desert dust (8%) Transportation (6%) Agriculture (4%)	**14 µg/m³:** Stated policies achieve reduction	No further analysis carried out	• No further analysis carried out
Western Asia and Eastern Europe	**16 µg/m³:** Residential (31%) Desert dust (22%) Power and industry (18%) Municipal solid waste (10%) Agriculture (9%)	**16 µg/m³:** Desert dust (23%) Power and industry (22%) Residential (17%) Transportation (12%) Municipal solid waste (12%)	**12 µg/m³:** Desert dust (32%) Power and industry (17%) Municipal solid waste (17%) Agriculture (14%) Transportation (10%)	• Residential • Further control of industrial emissions.
Latin America and the Caribbean	**9 µg/m³:** Desert dust (25%) Transportation (18%) Residential (16%) Power and industry (14%) Agriculture (11%)	**10 µg/m3:** Desert dust (24%) Transportation (18%) Residential (15%) Power and industry (14%) Agriculture (12%)	**7 µg/m³:** Desert dust (32%) Transportation (17%) Agriculture (13%) Municipal solid waste (13%) Power and industry (12%)	• Residential
Russia	**11 µg/m³:** Desert dust (27%) power and industry (20%) Residential (18%) Transportation (15%) Agriculture (11%)	**11 µg/m³:** Desert dust (27%) power and industry (22%) Transportation (16%) Agriculture (13%) Residential (12%)	**9 µg/m³:** Desert dust (34%) power and industry (17%) Transportation (15%) Agriculture (14%) Municipal solid waste (10%)	• Further control of industrial emissions
Northeast Asia	**27 µg/m3:** Power and industry (30%) Residential (19%) Agriculture (17%) Transportation (10%) Other (9%)	**25 µg/m³:** Power and industry (27%) Agriculture (19%) Transportation (13%) Municipal solid waste (13%) Other (10%)	**19 µg/m³:** Power and industry (27%) Agriculture (20%) Municipal solid waste (17%) Desert dust (10%) Residential (9%)	• Ending the open burning of agricultural residue
Middle East	**41 µg/m³:** Desert dust (76%) Power and industry (12%) Transportation (4%) Agriculture (3%)w Municipal solid waste (2%) Other (2%)	**42 µg/m³:** Desert dust (74%) Power and industry (10%) Transportation (6%) Agriculture (6%) Municipal solid waste (3%)	**34 µg/m³:** Desert dust (89%) Transportation (3%) Agriculture (2%) Municipal solid waste (2%) Other (2%)	• Further control of industrial emissions • Further controls of vehicle emissions

	Population-weighted $PM_{2.5}$ exposure in region, followed by top five key emission source categories contributing to population-weighted $PM_{2.5}$ exposure, 2020	Population-weighted $PM_{2.5}$ exposure in region, followed by top five key emission source categories contributing to population-weighted $PM_{2.5}$ exposure, Stated Policies scenario	Population-weighted $PPM_{2.5}$ exposure in region, followed by top five key emission source categories contributing to population-weighted $PM_{2.5}$ exposure, Integrated Policies scenario	Key priority reduction sectors under the integrated scenario to halve the number of people exposed to levels above 25 µg/m³ by 2040
Europe	**9 µg/m³:** Residential (33%) Transportation (23%) Power and industry (17%) Desert dust (12%) Agriculture (10%)	**6 µg/m³:** Stated policies achieve reduction	No further analysis carried out	• No further analysis carried out
Oceania	**8 µg/m³:** Power and industry (28%) Transportation (23%) Agriculture (21%) Other (10%) Residential (9%)	**11 µg/m³:** Power and industry (28%) Transportation (25%) Agriculture (20%) Residential (9%) Other (9%)	**8 µg/m³:** Power and industry (27%) Transportation (24%) Agriculture (18%) Other (10%) Residential (9%)	• Reduce emissions from livestock and fertilizer use
North America	**11 µg/m³:** Desert dust (27%)Agriculture (22%), Transportation (17%), Power and industry (16%), Residential (10%)	**7 µg/m³:** Stated policies achieve reduction	No further analysis carried out	• No further analysis carried out

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